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RAPID SET MATERIALS FOR ADVANCED SPALL REPAIR

Michael I. Hammons
Airbase Technologies Division
Air Force Research Laboratory
139 Barnes Drive, Suite 2
Tyndall Air Force Base, FL 32403-5323

Jeffrey C. Petermann and Athar Saeed
Applied Research Associates, Inc.
P.O. Box 40128
Tyndall Air Force Base, FL 32403-5323

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6. AUTHOR(S)
**Hammons, Michael I.; *Petermann, Jeffrey C.; *Saeed, Athar

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
*Applied Research Associates, P.O. Box 40128, Tyndall Air Force Base, FL 32403
**Air Force Research Laboratory, Materials and Manufacturing Directorate, Airbase Technologies Division, 139 Barnes Drive, Suite 2, Tyndall Air Force Base, FL 32403-5323

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Headquarters, Air Force Civil Engineer Support Agency
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14. ABSTRACT
The objective of this research was to evaluate rapid-set materials for use in deep spall repair. The evaluation process considered the following thermal and mechanical properties: elasticity, modulus of elasticity, creep, bond strength, compressive strength, tensile strength, modulus of rupture, and the coefficient of thermal expansion.

15. SUBJECT TERMS
pavement, spall repair, airfield damage repair, cementitious materials

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1. EXECUTIVE SUMMARY

This research evaluated rapid-set materials for use in deep spall repair. The evaluation process considered the following thermal and mechanical properties: elasticity, modulus of elasticity, creep, bond strength, compressive strength, tensile strength, modulus of rupture, and the coefficient of thermal expansion.

An initial series of experiments were performed on the following eleven rapid setting cementitious materials:

1. 10-61 Rapid Mortar
2. PavePatch 3000
3. Futura 15
4. Premium Patch
5. HD-50 Rapid Set
6. Rapid Set DOT Mix
7. PaveMend 15
8. SikaQuick 2500
9. PaveMend TR
10. Veraspeed
11. PaveMend VR

Methodic screening of each specimen was performed to determine early strength properties in a room-temperature environment. Testing intervals were established between 1.5 hours and 28 days to gain an appreciation for mechanical behavior over time. Four materials were down-selected for further study and ranked relative to their individual compressive, tensile and bond strengths. Additional testing on the remaining four materials included varying water content at 110-125% of recommended volume, temperature sensitivity trials between 40-100 °F, bond slant shear tests and linear shrinkage and coefficient of thermal expansion.

Samples of each material were also subjected to 1500 passes of the F-15 load cart. The F-15 load cart has a total mass of 32,500 lbs (14,741 kg) on a single tire inflated to 315.0 psi (21.7 bar).

Post-loading evaluations included crack mapping and bond strength testing by way of adhered hydraulic core pulling. Each material was placed into one of the three excavation methods – saw cutting, jack hammering and cold planing.

Of the four selected materials (10-61 Rapid Mortar, Futura 15, PaveMend 15, Rapid Set DOT Mix), the Rapid Set DOT Mix performed highest in both compressive and flexural strengths at the 24 hour time interval. Rapid Set DOT Mix also possessed the greatest slant shear and split tensile strengths at the same interval, but showed lower modulus of elasticity than the other materials.

SikaQuick 2500 performed well in initial tests, but did not receive further analysis due to budget constraints. Premium Patch was rated as the third best performing material of all eleven materials, while PaveMend 15 rated poorly throughout. The Rapid Set DOT Mix was the least sensitive to water and Futura 15 was the most sensitive of the final four materials.

Additionally, temperature sensitivity analysis showed that Rapid Set 10-61 and Futura 15 performed well under increased thermal loading, while the Rapid Set DOT Mix and PaveMend 15 were negatively affected by higher temperatures.

In summary, Rapid Set DOT Mix provides the best possible rapid spall repair of all materials tested during this study.

2. INTRODUCTION

2.1. Background

Spalling describes cracking, breaking, chipping, or fraying of a concrete slab near a joint or crack. Spalls may be caused by one or more of the following mechanisms:

- Durability issues such D-cracking and alkali-silica reaction (ASR).
- Inadequate maintenance, e.g., allowing foreign matter to collect in the joints.
- Improper construction procedures and details such as misaligned dowel bars, sawing joints too late, not sawing joints to adequate depth, or excessive working of the fresh concrete leading to a paste-rich mix.
- Fatigue caused by repeated mechanical loading of the joint by high-pressure aircraft tires.
- Damage from munitions.

Spalls may be partial or full depth. In the case of both full- and partial-depth spalls, foreign object debris (FOD) may be generated, and the rough surfaces at the spall may damage aircraft tires. Full-depth spalls reduce the structural capacity of the slab and exacerbate fatigue failure under repeated loading [1].

Spall repairs at expeditionary locations have failed sooner than expected based upon load test studies. Many of these repairs involve large, relatively non-uniformly shaped repairs that are loaded within a few hours after placement [2]. The service life of a spall repair is dependent on many factors such as the construction quality, repair material properties, and loading conditions. The most important factor is often the time required to construct a durable repair. Expedient repairs are made when time, equipment, and/or manpower is not available to install a permanent repair. As with any quick fix, there is often a tradeoff between expediency and quality. Rapid repairs extend the life of a pavement using more forgiving methods than those used in traditional repairs, but durability and long-term performance may suffer.

Because spall repair service life is influenced by many factors, Air Force civil engineers and airfield managers are often forced to make airfield maintenance decisions with only limited information on the expected performance of spall repairs. Spall repair performance curves that consider these factors would greatly assist airfield management decision makers in determining what types of repairs to make and when to make them.

2.2. Research Objective

The research objective was to determine the mechanical and bond characteristics of various rapid set materials for use in airfield spall repairs and methodically recommend one to represent the best possible combination of properties in a material for such repairs. An additional goal of testing was to identify the sensitivity of each material to increased water content and varying thermal conditions during curing in order to avoid potential strength loss and to ensure the highest quality final repair possible under field conditions.

3. LITERATURE REVIEW

3.1. Spall Repair Procedures

The normal procedure for repairing a spall is outlined in Engineering Technical Letter (ETL) 07-8 as follows [2]:

- Remove loose debris from the damaged area.
- Mark the outer edge of the repair (2 to 3 in beyond the damaged area).
    - The shape should be a rectangle or pentagon.
    - The aspect ratio should be less than two.
    - The largest dimension should be 8 ft (2.4 m) or less.
- Saw the edges of the repair to a depth of at least 2 in (50 mm).
- Do not feather the repair.
- Make additional cuts within the bounds of the repair edges using a concrete saw.
- Make transverse cuts on each end at 1.5 in (38 mm) from the ends of the repair.
- Remove the remaining material using a small jack hammer (30 pounds or less).
- Remove loose debris from the repair area.
- Wash the repair area with a high-pressure washer or use water and a scrub brush.
- Remove any loose material or lodged debris from the joint or crack.
- Place a small bead of caulk over the joint or crack.
- If using a cement-based repair material, soak the repair and leave saturated surface dry (SSD).
- Place a compressible insert material over any joint or crack in the repair area.
- Mix the materials in accordance with manufacturers' recommendations.
- A temperature gun (thermometer) should be used to check the temperature of the water and material before mixing, as well as the temperature of the material during mixing.
- Pour/place the material in the repair.
- Clean mixing and placement equipment immediately after use.
- When using cement repair materials, either wet cure or apply curing compound.
- Remove the compressible spacer insert after the repair has cured.
- Reseal the joint.

3.2. Concrete Repair Materials

In recent years, new repair materials have been introduced into the marketplace. The American Concrete Institute (ACI) 546.3R document lists the following broad categories of concrete repair materials [2]:

- Portland or blended cement-based mortar and concrete
- Portland or blended cement-based silica fume mortar and concrete
- Portland or blended cement-based polymer-cement mortar and concrete
- Magnesium-ammonium-phosphate-cement mortar and concrete
- Polymer-based mortar and concrete

Within each of these broad categories of repair materials, it is possible to find a wide variation in engineering properties. Manufacturers of these materials may change the formulations so that by

the time research studies have been completed, the results of the study do not reflect the properties of the new product [4].

The performance of a repair depends to a large extent on the behavior and compatibility of the repair material and the existing substrate as a composite system [4]. It is often difficult to find the engineering data needed to evaluate a product [2]. In some cases, engineering data for the product may not be provided by the manufacturer. In other cases, data are presented in terms of non-standard or modified test protocols making direct comparison of products problematic.

3.3. Properties of Repair Materials

The engineering properties of repair materials vary widely with each material. Speer [1] stated that finding an ideal material is difficult, because one material may excel in certain respects, it may be deficient in others. ACI 546.3R presents a discussion of properties that should be considered, and these are summarized in the following paragraphs:

3.3.1. Volume Stability

Volume stability refers to changes in the linear dimensions of the repair material. Most cementitious materials undergo volume change due to external and autogenous shrinkage in the first few hours and days after mixing. Differential volume change between the repair and substrate leads to shear stresses at the interface, and if these stresses exceed the bond strength, debonding can occur. If the bond remains intact, the restraint provided by the substrate may exceed the tensile strain capacity of the repair material resulting in relief cracking. Also, excessive expansion of the repair material can lead to “blow up” of the material within the repair.

3.3.2. Mechanical Properties

Mechanical properties reveal a material’s elastic and inelastic behavior when a load is applied. It is usually unnecessary for the repair material to have mechanical properties in excess of the substrate. However, if some of the mechanical properties are vastly different than those of the substrate, problems may ensue. For example, large differences in stiffness between the repair material and substrate may lead to stress concentrations which break the bond at the interface between the repair and substrate materials. Important mechanical properties include the following:

- **Post Loading Elasticity –** The ability of a material to regain its size and shape after removal of a load.
- **Modulus of Elasticity –** The stiffness of a material measured as the ratio of the normal stress to normal strain in the elastic regime.
- **Creep –** Time-dependent deformation due to sustained load.
- **Bond Strength –** The resistance to separation between the repair material and the substrate.
- **Compressive Strength –** The resistance of a material to compressive load.
- **Tensile Strength –** The resistance of a material to tensile load.
- **Modulus of Rupture (Flexural Strength) –** The resistance of a material to bending; estimates to tensile strength.
- **Coefficient of Thermal Expansion –** The change in linear dimension per unit linear dimension of a material with a unit change in temperature.

3.3.3. Durability

Durability is the resistance to weathering action, chemical attack, abrasion, and alkali-aggregate reactions, and other degradation mechanisms. Because this research is primarily concerned with short-term performance of the repair in dry, non-freeze/thaw environments, the material durability is not directly addressed.

4. RESEARCH APPROACH

4.1. Test Plan

This study chose and evaluated eleven commercially-available rapid-setting repair materials. Early strength development was determined for all eleven materials at room temperature following the manufacturer's recommendations for mixing.

4.1.1. Engineering Properties Screening Tests

Table 1 summarizes the strength tests and sample sizes. From the start mixing, three samples were tested at 1.5 hours, 2 hours, 3 hours, 4 hours, 24 hours and 28 days intervals.

Table 1. Engineering Properties Tests and Sample Sizes

Strength Parameter and Testing Protocol	Sample Size
Compressive strength ASTM C39	3-in diameter × 6-in long cylinder
Flexural strength ASTM C78	3-in wide × 16-in long beam × 4-in thick beam
Splitting tensile strength ASTM C496	3-in diameter × 6-in long cylinder
Slant shear bond strength ASTM C882	3-in diameter × 6-in long cylinder
Modulus of elasticity ASTM C469	3-in diameter × 6-in long cylinder

*American Society for Testing and Materials (ASTM)

4.1.2. Down-Selection of Materials for Detailed Testing

Based upon the given budget and the final results of initial testing, four materials that represented a wide range of performance were down-selected for further study. Materials were ranked according to relative compressive strength, slant shear bond strength and flexural strength as shown in Figure 1. The flowchart shown in Figure 2 outlines the selection criterion and experimental approach. Materials were grouped into high, moderate, and low categories for compressive strength, flexural strength, and slant shear bond strength. Table 2 and Table 3 provide the material performance matrix details and ranking logic for all materials tested.

		Flexural Strength	Compressive Strength		
			H	M	L
Bond Strength	H	H	X		
		M		X	
		L			
	L	H			
		M		X	
		L			X

Figure 1. Research Factorial

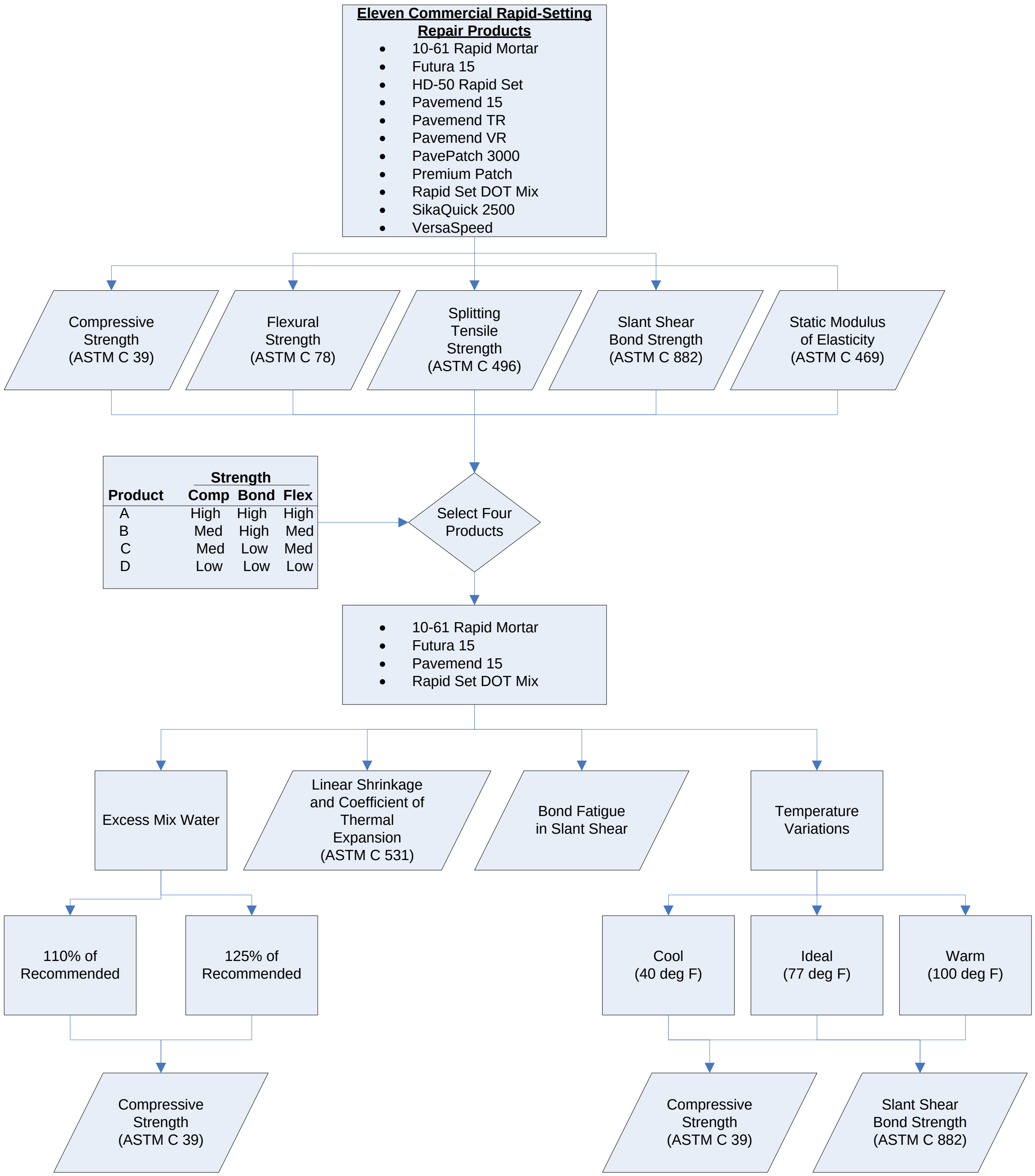

Figure 2. Research Approach and Testing Flowchart

Table 2. Material Performance Selection Matrix

Product	Compressive Strength	Slant Shear Bond Strength	Flexural Strength
A	High	High	High
B	Moderate	High	Moderate
C	Moderate	Low	Moderate
D	Low	Low	Low

Table 3. Material Ranking Logic

Descriptor	Compressive Strength	Slant Shear Bond Strength	Flexural Strength
High	Greater than 2,500 psi at 2 hours or less	Greater than 800 psi at 1.5 hours	Greater than 700 psi at 1.5 hours
Moderate	Greater than 2,000 psi at 4 hours or greater than 4,000 psi at 24 hours	Greater than 1,000 psi at 24 hours	Greater than 500 psi at 24 hours
Low	Less than 3,000 psi at 24 hours	Less than 600 psi at 24 hours	Less than 450 psi at 24 hours

4.1.3. Temperature Sensitivity Studies

Additional tests included compressive strength development at varying water contents and temperatures. Compressive strength tests were performed in accordance with ASTM C39 on the four selected spall repair materials at variable temperatures and storage conditions listed in Table 4. Three 3-in diameter × 6-in long cylinders were prepared for each time interval and each test.

4.1.4. Mix Water Content Sensitivity Studies

Compressive strength tests were performed in accordance with ASTM C39 on the four selected spall repair materials at mix water contents of 110 percent and 125 percent of the manufacturer's recommendations. Each material sample was prepared neat and stored at room temperature until the appropriate test time interval. The ages of loading were 1½, 2, 3, 4, and 24 hours. Three 3-in diameter × 6-in long cylinders were prepared and tested for each water content and age of loading.

Table 4. Temperature Sensitivity Test Matrix for Each Tested Material

Run Order	Age, hrs	Storage Temperature, °F	Mix Temperature, °F
1	13.0	77	77
2	15.5	100	100
3	24.0	77	77
4	24.0	100	40
5	12.0	40	77
6	1.50	77	100
7	24.0	40	100
8	1.50	40	40
9	10.5	77	40
10	24.0	40	40
11	1.50	100	77
12	1.50	40	100
13	13.0	77	77
14	15.5	100	100
15	24.0	77	77
16	24.0	100	40
17	12.0	40	77
18	1.50	77	100
19	24.0	40	100
20	1.50	40	40

4.1.5. Fatigue Tests

Fatigue testing of the spall repair bond was performed on slant shear bond specimens prepared from the four selected spall repair materials at room temperature. The purpose of the testing was to induce bond failure by repeated slant shear loading of a sample prepared with ordinary Portland cement (OPC) and a spall repair material. Stress levels were based upon the ultimate slant shear bond strength at 28 days determined at room temperature. All fatigue tests cylinders were subjected to a pre-load applied at the ages shown in Table 5 to simulate early traffic loading. Each sample was fatigue tested in AFRL's servo controlled 400,000 lbf compression test frame at 28 days or more. There were four materials and 16 test conditions per material for a total of 64 fatigue tests.

Table 5. Fatigue Test Matrix

Run Order	Preload Age, hrs	Stress Ratio
1	14	0.70
2	24	0.91
3	3	0.95
4	14	0.45
5	3	0.70
6	3	0.45
7	14	0.95
8	24	0.49
9	14	0.70
10	24	0.91
11	3	0.95
12	14	0.45
13	3	0.70
14	3	0.45
15	14	0.95
16	24	0.49

Samples were prepared and tested following the outline below for each of the four materials:

1. After the typical concrete slant shear samples have cured for 28 days, the sample was completed by preparing the repair material and placing into a cylinder mold to bond with the concrete substrate.
2. The cylinders prepared in step 1 were pre-loaded at time intervals shown in Table 5. The time intervals were measured from the start of mixing and not from final set. A cyclic compressive pre-load with a maximum compressive stress equivalent to the tire pressure of a C-17 (138 psi, or 975 lbs for a 3-in-diameter cylinder) were applied ten times at the appropriate time interval as shown in Figure 3. After the pre-load was applied, the samples were stored at room temperature and tested after at least 28 days measured from mixing time of the spall repair material to determine early loading affect on fatigue life.
3. During fatigue testing, the maximum load was defined by the stress ratio given in Table 5. The minimum load was a stress ratio of approximately 0.05.
4. Testing continued until failure of the bond between the spall repair material and the concrete substrate. The number load cycles at bond failure was recorded.

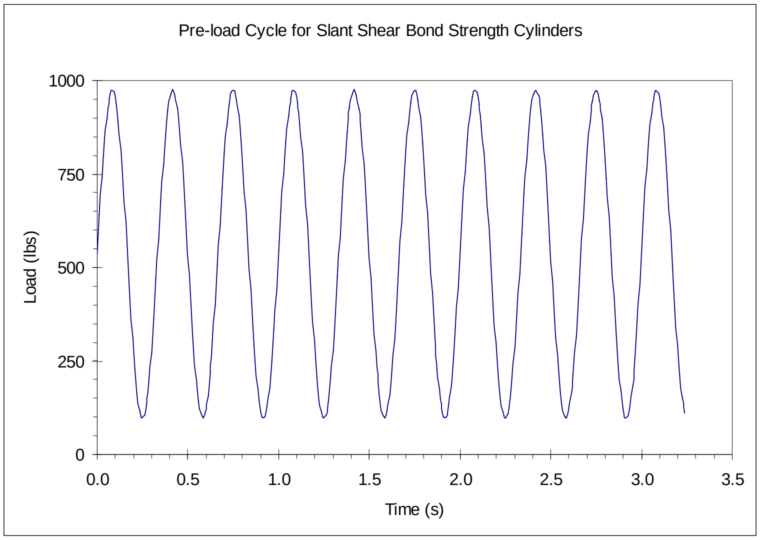

Figure 3. Pre-Load Cycles for Fatigue Tests

4.1.6. Simulated Aircraft Trafficking

An F-15 load cart with wheel load of 32,500 lbs (315 psi tire pressure) was used to traffic edge and corner spall repairs for a total of 1,500 passes. A photograph of AFRL's F-15 load cart is shown in Figure 4.

A total of three spall repairs were prepared for each of the selected materials. The edge and corner spall repairs to be trafficked were approximately 12 in wide, 30 in long and 2 in deep as shown in Figure 5. The untrafficked repairs, as shown in the same figure, were approximately 24 in wide, 30 in long and 2 in deep. Photographs of typical corner, edge, and untrafficked spall repairs are presented in Figure 6 through 8, respectively.

Figure 4. F-15 Load Cart

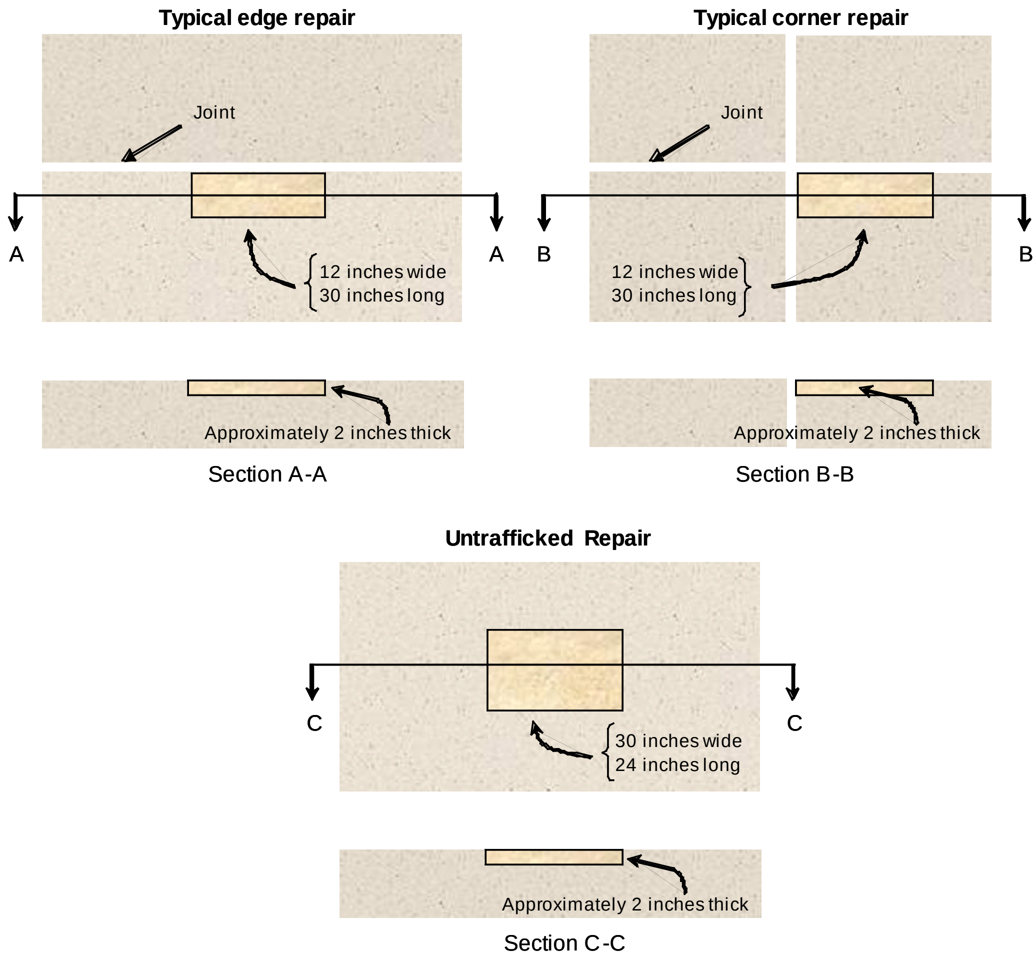

Figure 5. Diagram of Spall Repair Test Articles

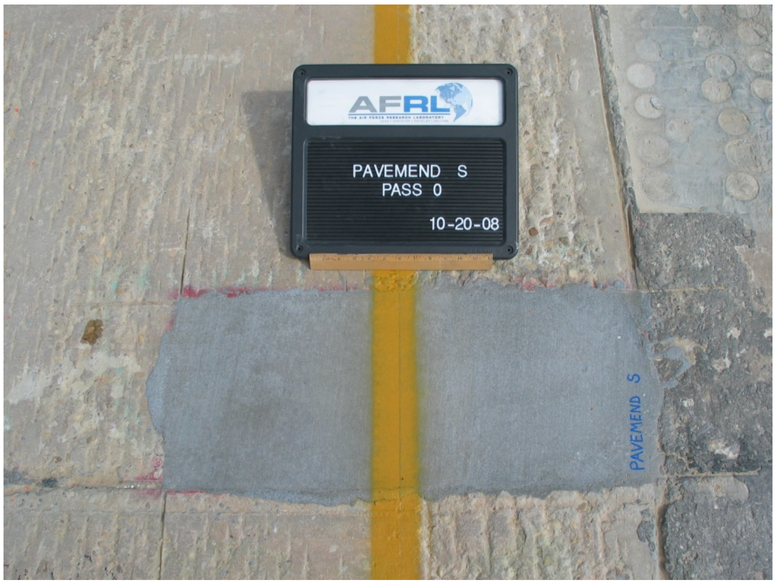

Figure 6. Typical Corner Spall Repair

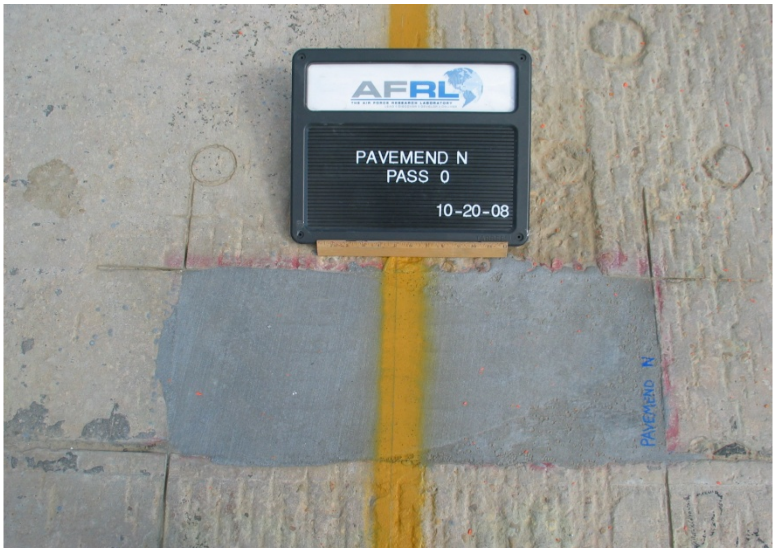

Figure 7. Typical Edge Spall Repair

Figure 8. Typical Interior Spall Repair (Not Trafficked)

4.2. Repair Materials

Eleven commercial repair materials were included in the study. Mechanical property tests were performed for each of these materials. Representative materials were selected for further beam fatigue tests and load cart tests. A brief description of each repair material is presented below.

4.2.1. Futura-15

Futura-15 is a cementitious material manufactured by W.R. Meadows designed for horizontal applications. It consists of a proprietary blend of selected cements, graded sands and chemical additives. Portland cement comprises 25 to 30 percent of the blend [6]. Repair areas should be a

minimum thickness of 1/2 in. Futura 15 may be extended up to 50 percent by weight with 3/8 in aggregate or larger [7].

4.2.2. HD-50

Dayton Superior HD-50 is a flowable fiber-reinforced repair mortar. The minimum application thickness is 1/2 in. For repairs thicker than 2 in,, the mortar should be extended by up to 60 percent by weight of 3/8 in aggregate [8].

4.2.3. Pave Patch-3000

Pave Patch-3000 is a specialty formulated patching material for concrete pavement repairs. It sets fast, develops high early strength and expands slightly. The minimum application thickness is 1/8 in. For repairs greater than 2 in thick, the mortar should be extended by up to 60 percent by weight of 3/8 in aggregate [9]. Pave Patch-3000 is manufactured by Dayton Superior and is primarily composed of 50 to 75 percent Quartz and 10 to 25 percent Portland cement [10].

4.2.4. Premium Patch

Premium Patch is a fast-setting, fiber-reinforced high strength cement based repair mortar. Its primary ingredients include 30 to 50 percent Portland cement and 40 to 60 percent Crystalline Silica [11]. A minimum patch depth of 1/2 in is required and the material must be extended 60 percent by weight with 3/8 in aggregate for repairs greater than 2 in [12].

4.2.5. SikaQuick 2500

SikaQuick 2500 is a blend of selected Portland cements, specially graded aggregates, admixtures for controlling set time, water reducers for workability and an organic accelerator [13]. SikaQuick 2500 is manufactured by the Sika Corporation and is used as a very rapid-setting, early strength gaining, cementitious patching material for concrete. The minimum application thickness for SikaQuick 2500 is 1/4 in as a mortar of 1 in when extended with 3/8 in aggregate [14].

4.2.6. Versaspeed

Versaspeed is a Portland cement based product manufactured by The Euclid Company. The product is composed of approximately 60 percent or more of Crystalline Silica/Quartz, 7 to 13 percent Portland cement, 5 to 10 percent amorphous silica, 5 to 10 percent aluminum oxide, and 5 to 10 percent calcium oxide [15]. Versaspeed is designed to be used as a rapid setting, patching and repair compound for horizontal, form and pour repair projects that range from 1/4 in to 6 in in thickness. Versaspeed may be extended up to 50 percent by weight using No. 8 aggregate [16].

4.2.7. PaveMend 15, PaveMend TR, and PaveMend VR

PaveMend is a cementitious, rapid setting structural repair mortar manufactured by CeraTech, Inc. (CTI). The chemical bonding process utilizes a large amount of recovered raw materials such as ash from coal and municipal solid waste processes [17]. CTI manufactures many blends of PaveMend with various properties and intended applications. The blends used in this study include PaveMend 15, PaveMend TR, and PaveMend VR. PaveMend 15 is a self leveling mortar intended to be used on horizontal structures. PaveMend TR is a trowelable, semi-leveling mortar designed for grades ranging from horizontal to 60 percent. Vertical and overhead repairs can be

made with PaveMend VR. Both PaveMend VR and TR can be extended with 3/8 in aggregate while PaveMend 15 cannot be extended. The minimum profile thickness of all three PaveMend products is 1/16 in [18].

4.2.8. 10-61 Rapid Mortar

The primary components of 10-61 Rapid Mortar include 40 to 70 percent Crystalline Quartz/Silica, 10 to 30 percent alumina cement and 1 to 10 percent Portland cement [19]. 10-61 Rapid Mortar is manufactured by BASF Building Systems. The material is designed for repairing horizontal surfaces and can be extended up to 100 percent with 3/8 in aggregate. 10-61 Rapid Mortar requires 5.5 pints of water per 50 pound bag and the minimum application thickness is 0.5 in [20].

4.2.9. Rapid Set DOT Repair Mix

Rapid Set DOT Repair Mix is a blend of propriety cements, ASTM concrete grade sand, air entrainment and a high range water reducer. It can be used neat for applications from 1/2 to 4 in thick or up to 24 in thick when extended up to 100 percent with a concrete grade coarse aggregate. It is not recommended to use this product in lifts [21]. Rapid Set DOT Repair Mix is manufactured by CTS Cement.

5. RESEARCH RESULTS

5.1. Strength Development at Ideal Conditions

The strength development of all eleven materials was determined at ideal conditions. Ideal conditions represent manufacturer-recommended practices and preparation and storage at room temperature.

5.1.1. Compressive Strength, ASTM C39

Figure 9 displays the compressive strength development for each material. Rapid Set DOT Mix, SikaQuick 2500, Premium Patch and HD-50 Rapid Set gained greater than 2,500 psi compressive strength in 2 hours or less. These materials achieved the most rapid compressive strength gain. Pave Patch-3000, PaveMend TR and PaveMend 15 exhibited the slowest strength gain and did not achieve more than 2,700 psi in 24 hours.

5.1.2. Slant Shear Bond Strength, ASTM C882

Figure 10 summarizes the slant shear bond strength development. SikaQuick 2500, Rapid Set DOT Mix, 10-61 Rapid Set and HD-50 Rapid Set achieved greater than 800 psi slant shear bond strength at 1.5 hours. All of the PaveMend materials and Futura 15 failed to achieve greater than 600 psi slant shear bond strength after 24 hours.

5.1.3. Flexural Strength, ASTM C78

Figure 11 shows flexural strength development. SikaQuick 2500, Premium Patch and Rapid Set DOT Mix achieved greater than 700 psi flexural strength at 1.5 hours. PaveMend VR and PaveMend 15 achieved less than 450 psi flexural strength after 24 hours. All of the PaveMend TR samples adhered to the molds and could not be tested.

5.1.4. Split Tensile Strength, ASTM C496

Figure 12 shows the split tensile strength development. Rapid Set DOT Mix, SikaQuick 2500 and Premium Patch achieved a split tensile strength of 350 psi or greater in 2 hours or less. Versaspeed, PaveMend TR and PaveMend 15 gained less than 150 psi split tensile strength after 24 hours. Futura 15 samples broke before testing could be completed at all time intervals.

5.1.5. Static Modulus of Elasticity, ASTM C469

Figure 13 shows the Modulus of Elasticity at ideal conditions for each material.

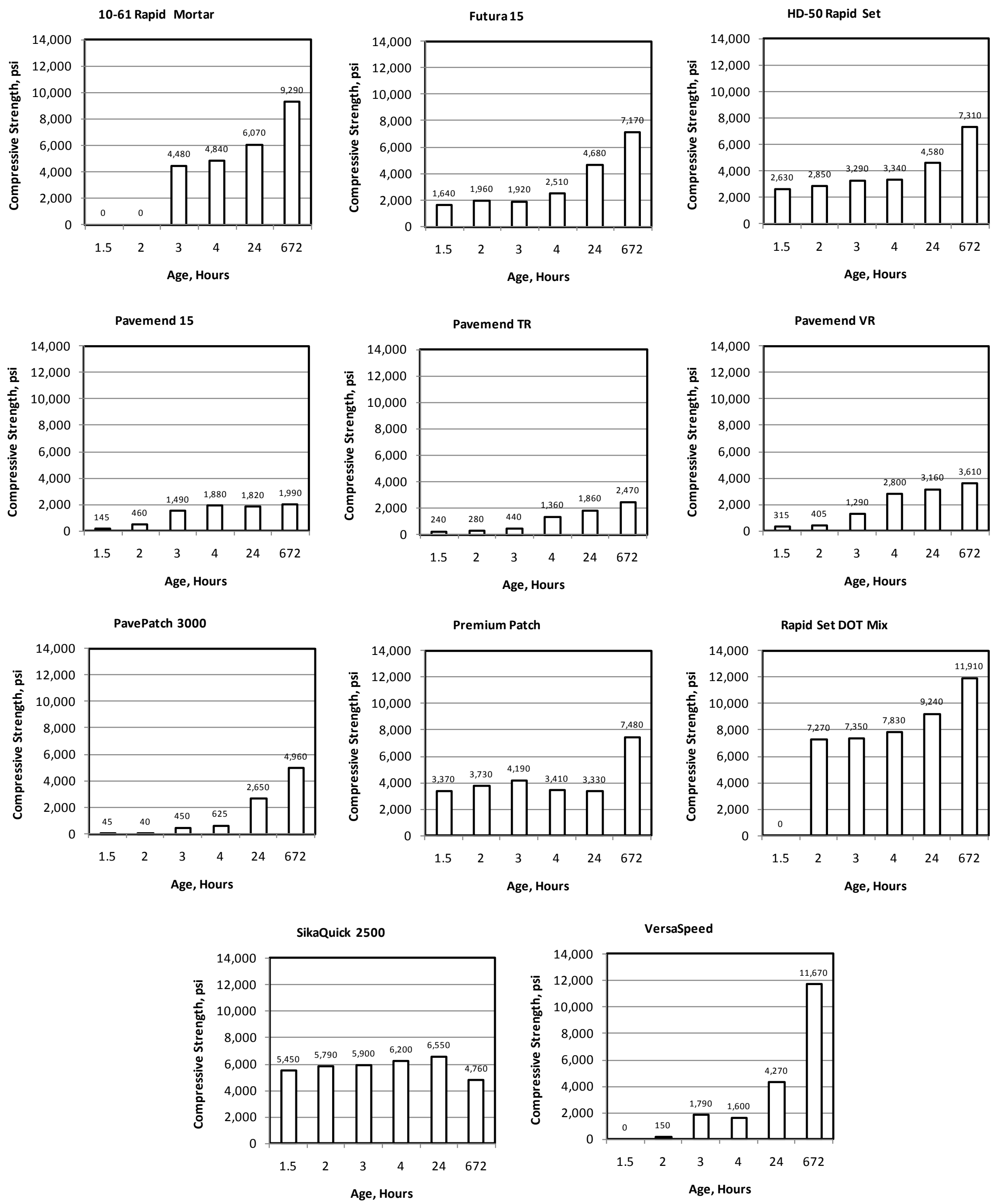

Figure 9. Compressive Strength at Ideal Conditions

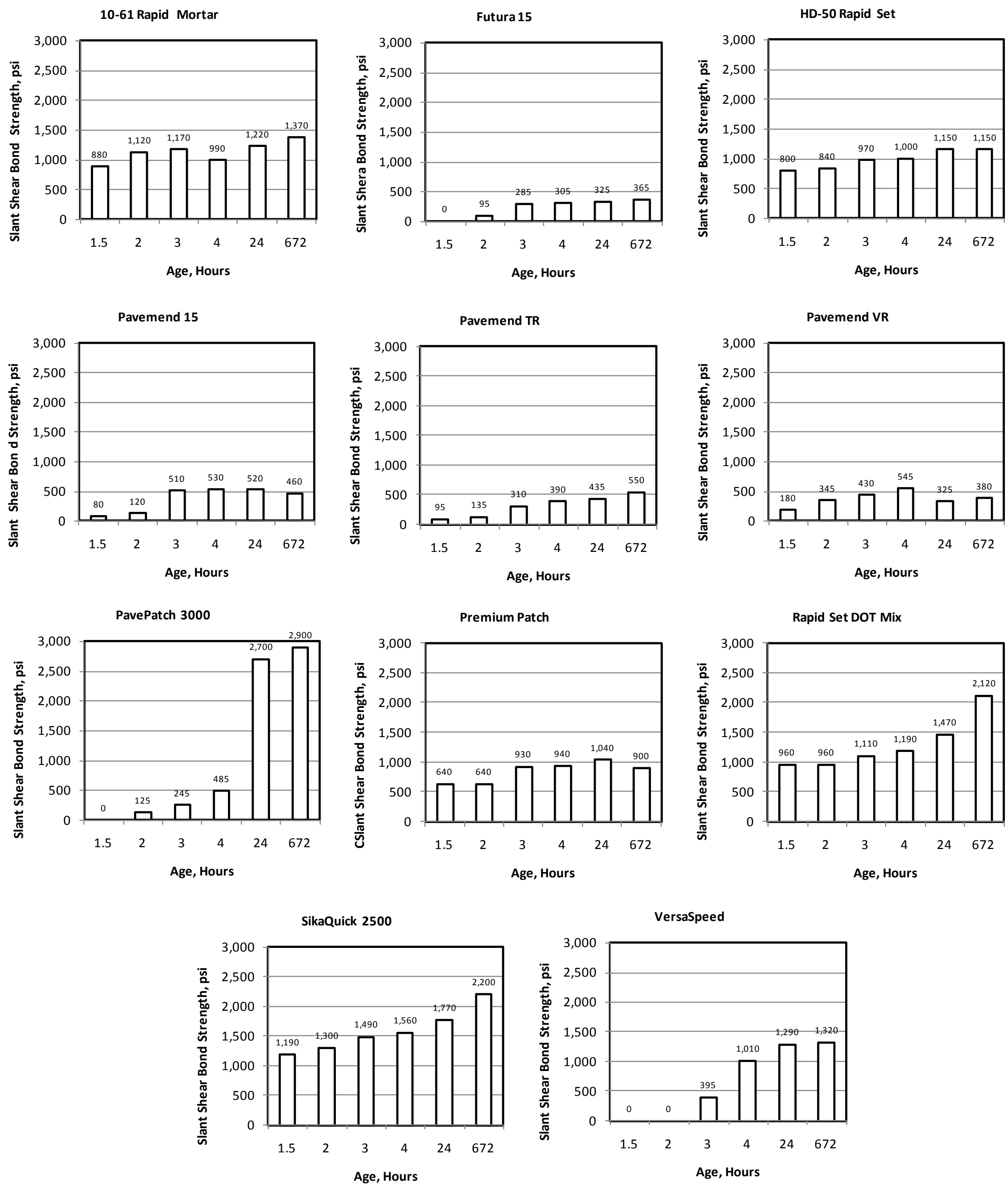

Figure 10. Slant Shear Bond Strength at Ideal Conditions

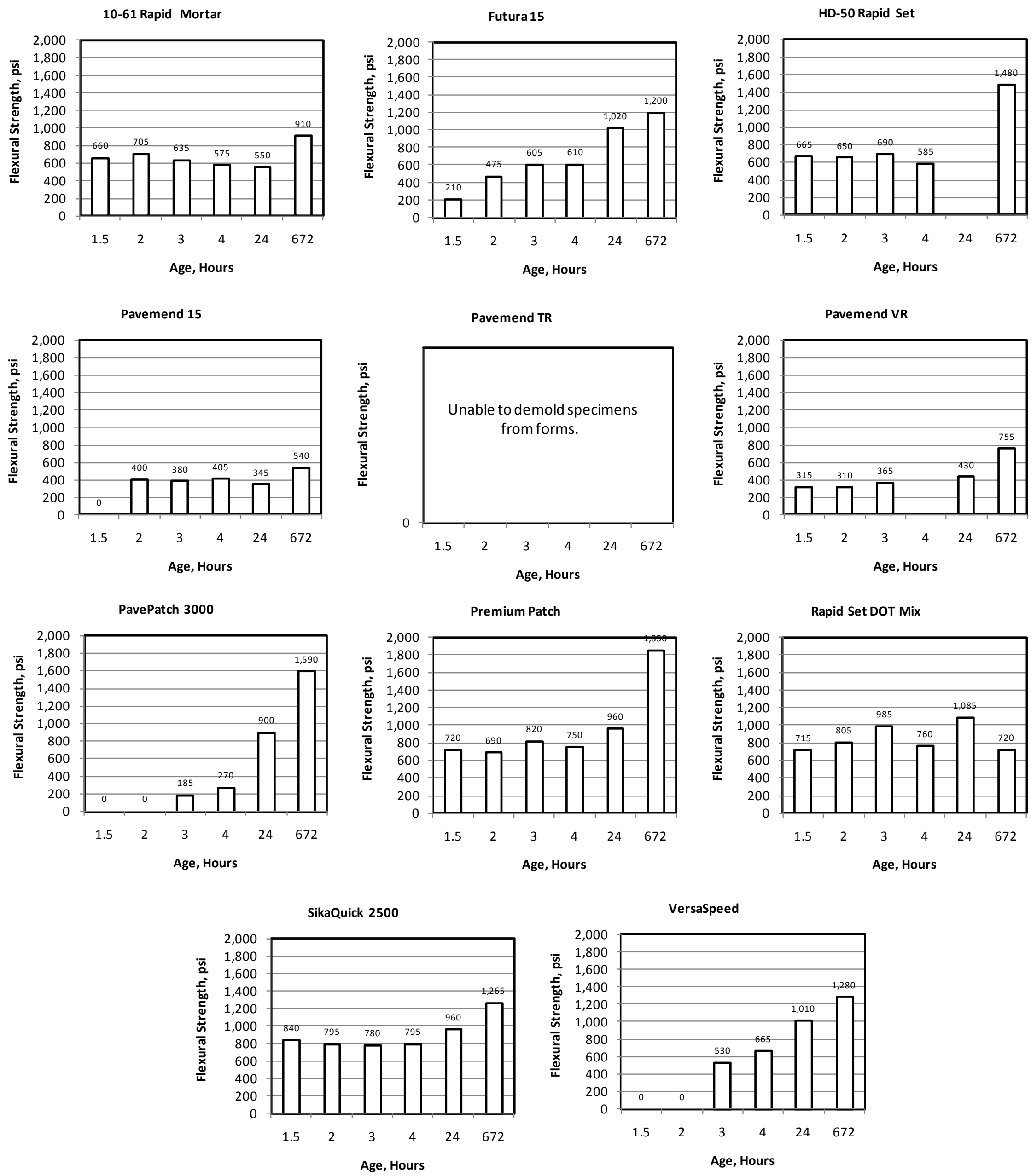

Figure 11. Flexural Strength at Ideal Conditions

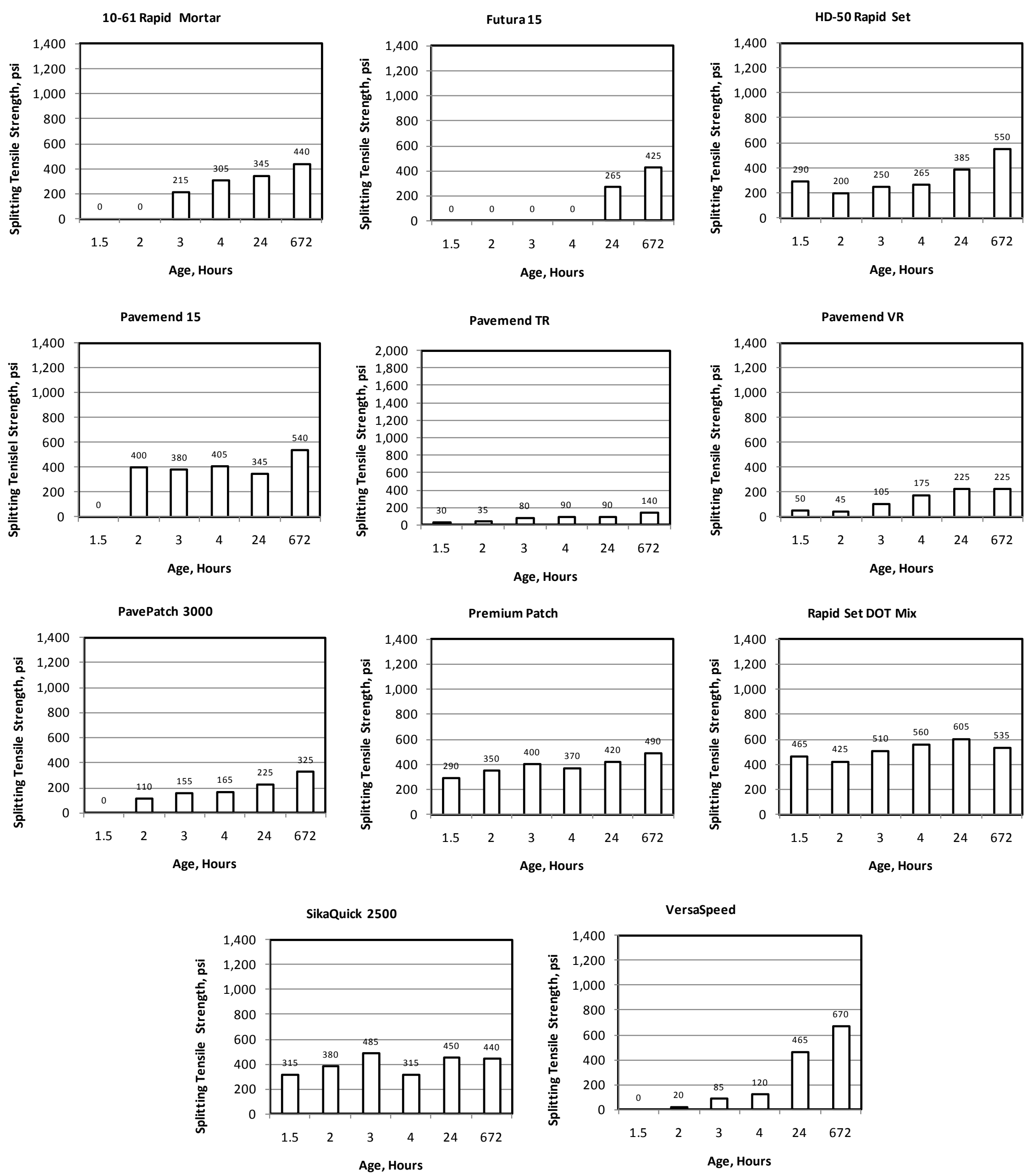

Figure 12. Split Tensile Strength at Ideal Conditions

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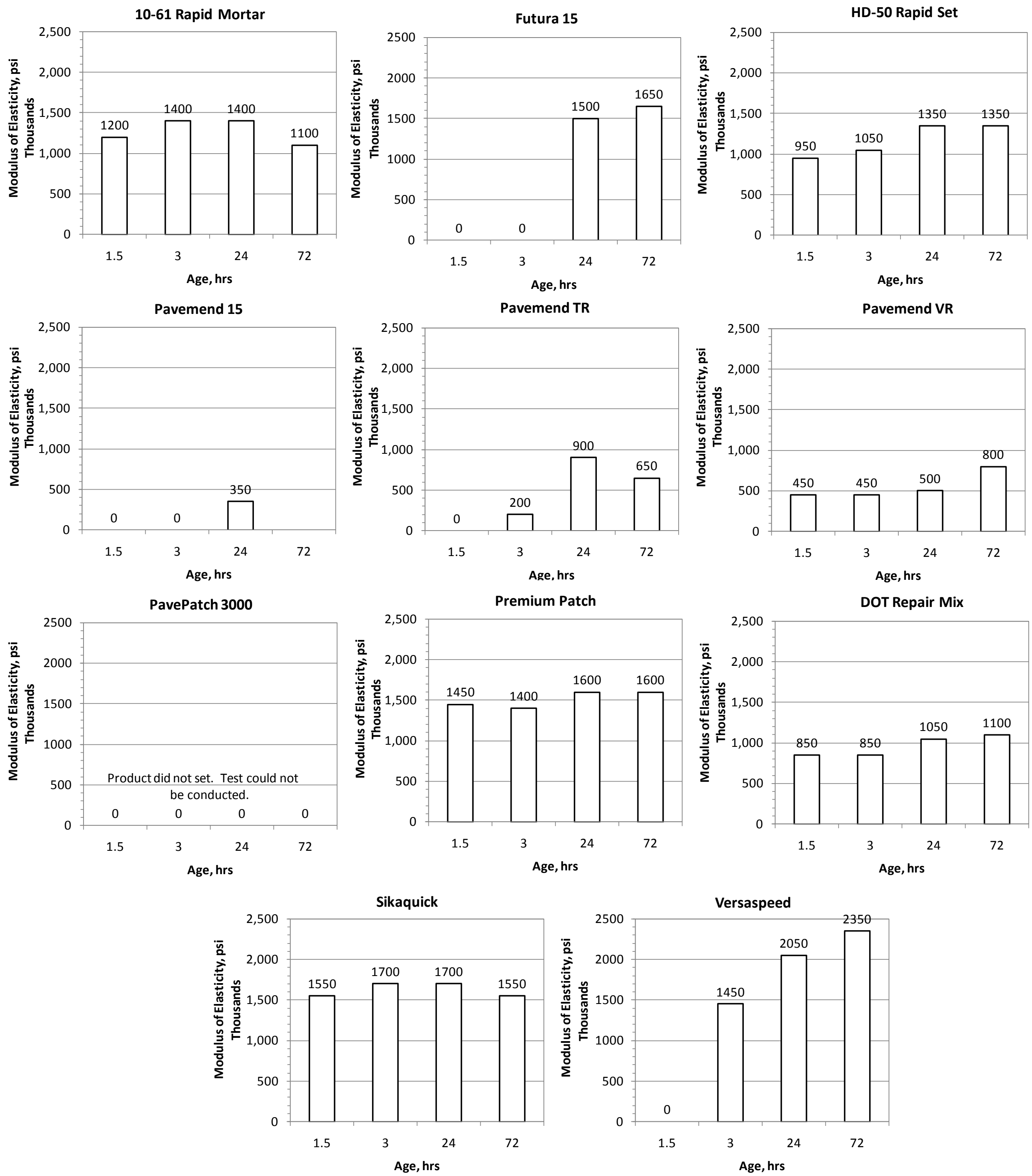

Figure 13. Modulus of Elasticity at Ideal Conditions

5.1.6. Summary of Material Performance at Ideal Conditions

The results of test rankings are summarized below in Table 6.

Table 6. Material Performance Ranking

Material	Compressive Strength	Slant Shear Bond Strength	Flexural Strength
SikaQuick 2500	High	High	High
Rapid Set DOT Mix§	High	High	High
Premium Patch	High	Moderate	High
HD-50 Rapid Set	High	High	Moderate
10-61 Rapid Set§	Moderate	High	Moderate
VersaSpeed	Moderate	Moderate	Moderate
Futura 15§	Moderate	Low	Moderate
PavePatch 3000	Low	Moderate	Moderate
PaveMend VR	Moderate	Low	Low
PaveMend TR	Low	Low	Low
PaveMend 15§	Low	Low	Low
§ Indicates product selected for further testing.			

5.1.7. Compressive, Flexural and Bond Strength Relationships

Linear regression models were developed using the data from the 3, 4, and 24 hour tests to estimate flexural and bond strengths from compressive strength. Flexural strength is often related to the square root of compressive strength; therefore, the following relationship was selected for the models:

$$f_n = \alpha\sqrt{f_c} + \beta \qquad (1)$$

where,

f_n = flexural strength (f_f) or bond strength (f_b) in psi

f_c = compressive strength in psi

α, β = regression coefficients

Figure 14 shows the data and regression model for flexural strength as a function of compressive strength. The solid line in the graph represents the regression model given by

$$f_f = 9.61\sqrt{f_c} - 75.8 \qquad (2)$$

Note that all units in this regression equation are shown in psi. The dashed lines in the graph show the 95 percent confidence interval on the regression. These lines indicate that there is great confidence in the prediction of the bond strength from compressive strength near the middle of the plot, where the square root of compressive strength lies between about 40 and 80 psi, corresponding to a compressive strength of approximately 1,600 to 6,400 psi.

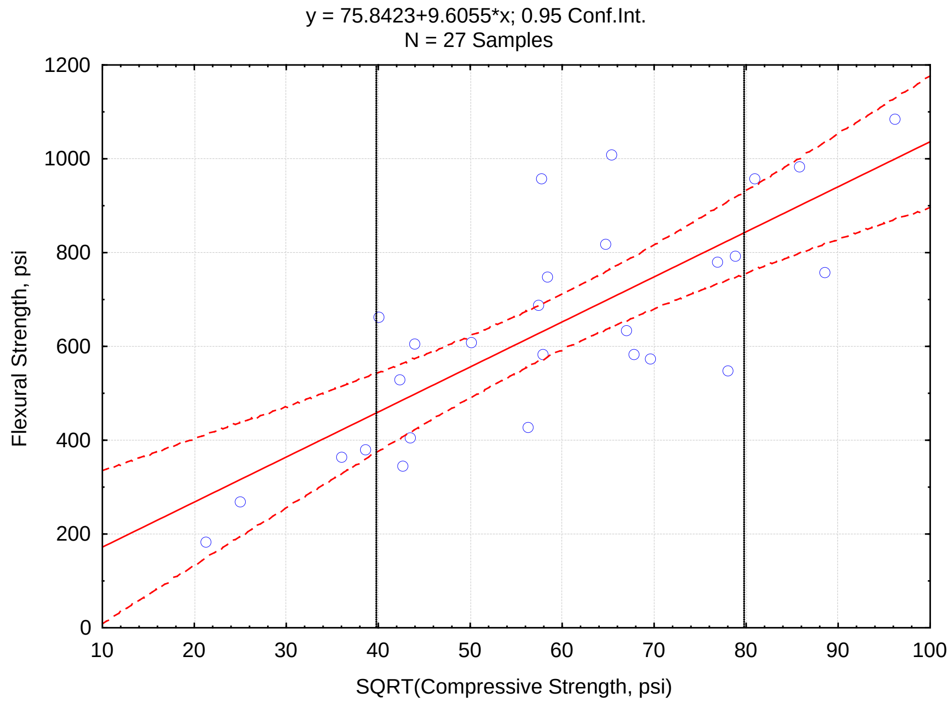

Figure 14. Relation between Compressive Strength and Flexural Strength (3, 4, and 24 hours)

Figure 15 shows the data and regression model for slant shear bond strength as a function of compressive strength. The solid line in the graph represents the regression model given by

$$f_b = 18.6\sqrt{f_c} - 184 \tag{3}$$

Note that all units in this regression equation are psi. Again, the dashed lines in the graph show the 95 percent confidence interval on the regression.

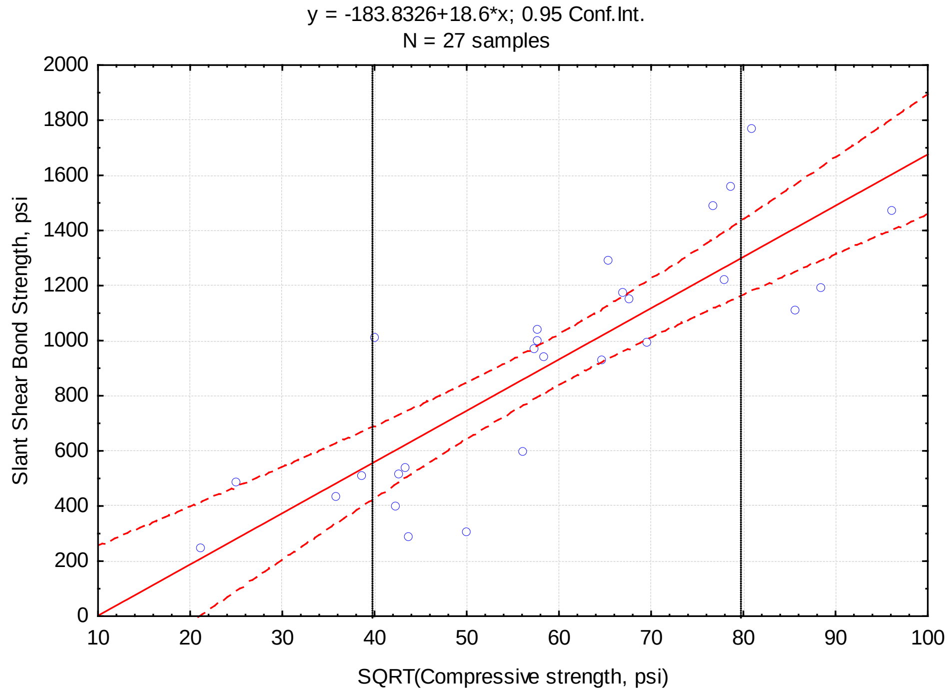

Figure 15. Relation Between Compressive Strength and Bond Strength (3, 4, and 24 hours)

5.2. Strength Development with Variable Water

The four materials selected from Table 6 were prepared with water contents that equaled 110 percent and 125 percent of the manufacturer's recommendations. Each material sample was prepared and stored at room temperature until the appropriate test time interval. The results of compressive strength tests conducted in accordance with ASTM C39 are presented in Figures 16 through 19 for the four products. In these figures, the bar charts represent the average compressive strength values, while the error bars represent 95 percent confidence intervals on the mean.

These data indicate that all four materials are sensitive to increases in mix water content, and that strength is significantly reduced, particularly at early ages, by increasing the mix water above that recommended by the manufacturer. These findings were expected, because these trends are true for most cementitious materials, i.e., increasing the water-cementitious ratio has a detrimental effect on strength. Of the four materials tested, Rapid Set DOT Mix (Fig. 16) was the least sensitive to an increase in mix water, and Futura 15 (Fig. 17) was the most sensitive.

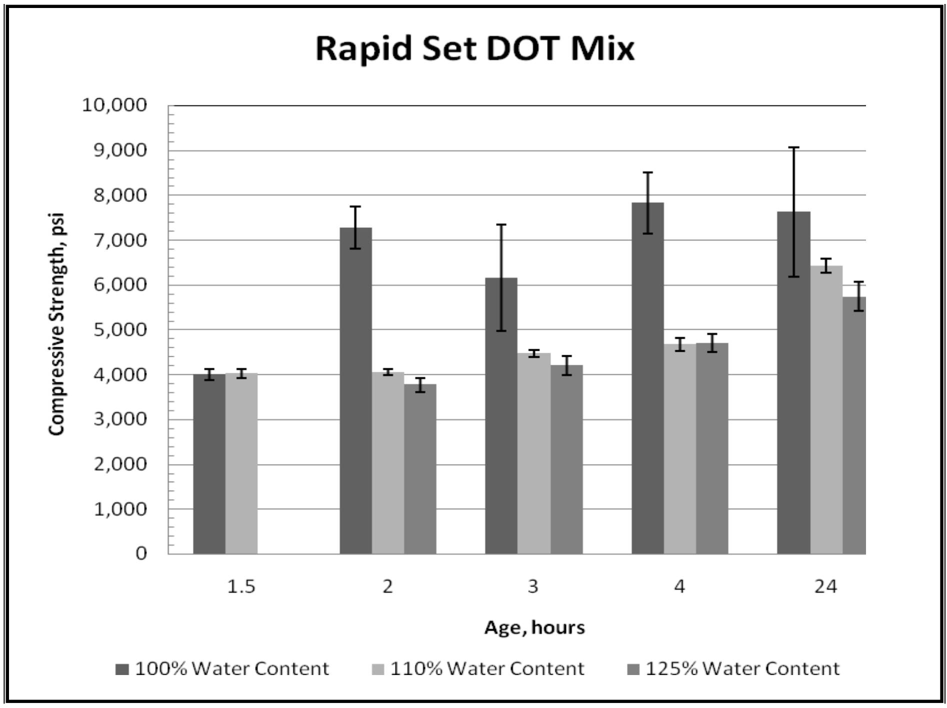

Figure 16. Rapid Set DOT Mix Compressive Strength with Variable Water

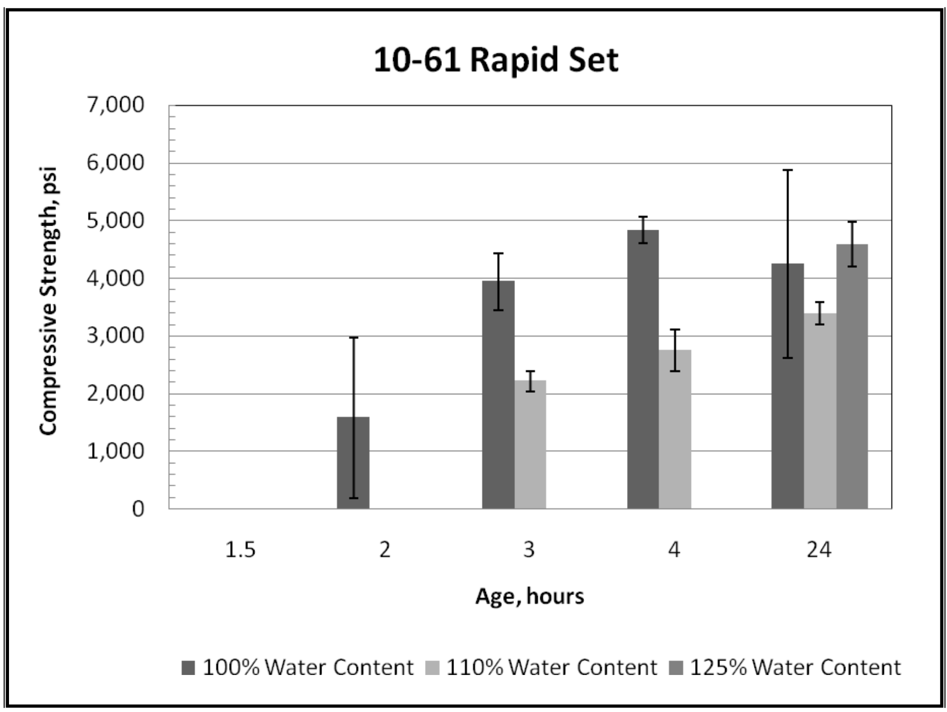

Figure 17. 10-61 Rapid Set Compressive Strength with Variable Water

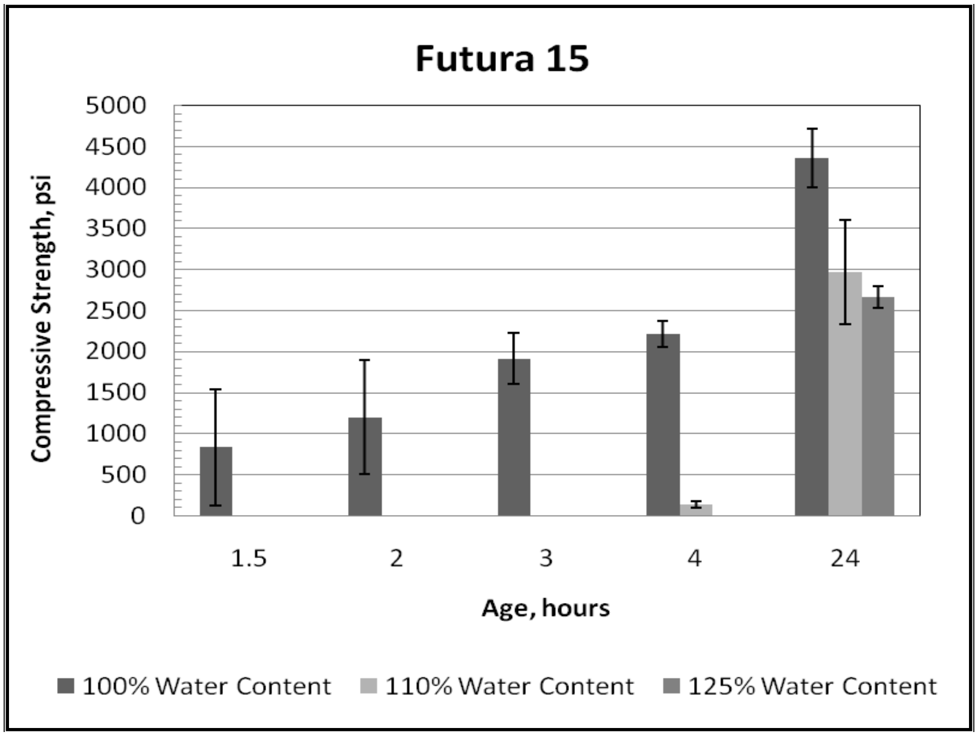

Figure 18. Futura 15 Compressive Strength with Variable Water

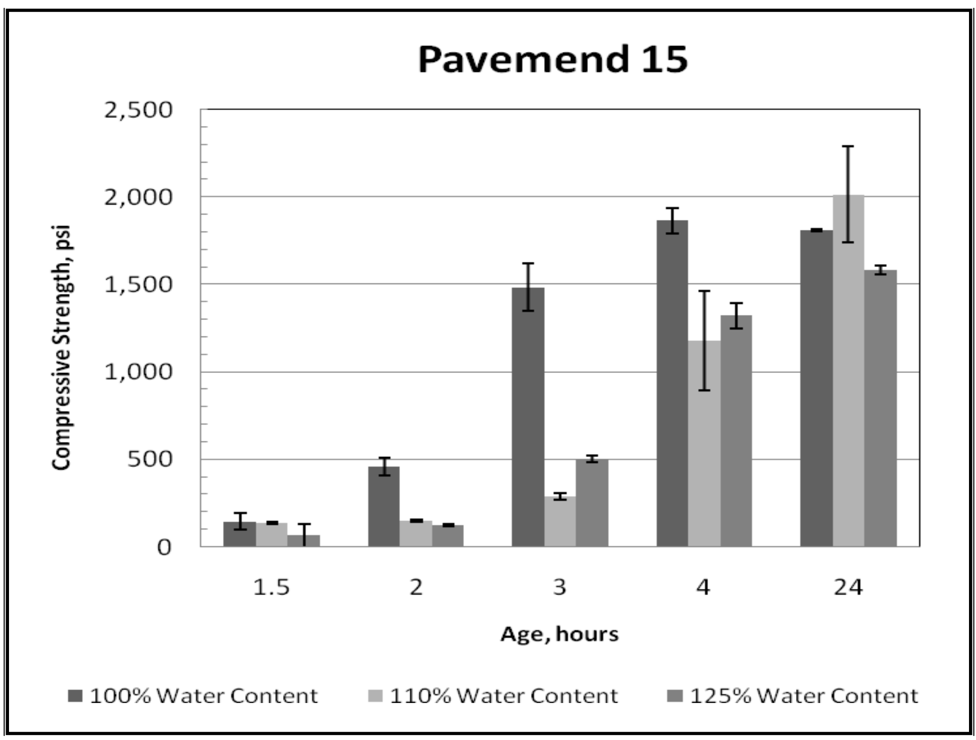

Figure 19. PaveMend 15 Compressive Strength with Variable Water

5.3. Temperature Sensitivity

Temperature sensitivity tests were conducted on the four materials selected from Table 6. An experiment was designed using the I-Optimal Design Assistant™ from Objective Design of Experiments Math Options, Inc. [22]. The dependent variables in the experiments were compressive strength (ASTM C39) and slant shear bond strength (ASTM C882). The results of these experiments are presented in Table 7 through Table 10.

Table 7. Temperature Sensitivity Data, 10-61 Rapid Set

Run Order	Age, hrs	Curing Temperature, °F	Mix Temperature, °F	10-61			
				Compressive		Slant Shear Bond	
				Load, lbs	Stress, psi	Load, lbs	Stress, psi
1	13.0	77.0	77.0	11,010	1,560	11,650	825
2	15.5	100.0	100.0	12,070	1,710	13,110	930
3	24.0	77.0	77.0	11,210	1,585	11,480	810
4	24.0	100.0	40.0	6,730	950	9,540	675
5	12.0	40.0	77.0	9,870	1,395	9,430	665
6	1.5	77.0	100.0	500	70	0	0
7	24.0	40.0	100.0	12,410	1,755	11,420	810
8	1.5	40.0	40.0	0	0	0	0
9	10.5	77.0	40.0	11,620	1,645	10,240	725
10	24.0	40.0	40.0	9,020	1,275	8,770	620
11	1.5	100.0	77.0	9,660	1,365	9,740	690
12	1.5	40.0	100.0	0	0	0	0
13	13.0	77.0	77.0	12,300	1,740	12,220	865
14	15.5	100.0	100.0	11,760	1,665	11,830	835
15	24.0	77.0	77.0	14,640	2,070	14,780	1,045
16	24.0	100.0	40.0	8,890	1,260	10,570	750
17	12.0	40.0	77.0	11,630	1,645	10,490	740
18	1.5	77.0	100.0	1,430	200	0	0
19	24.0	40.0	100.0	13,680	1,935	13,860	980
20	1.5	40.0	40.0	0	0	0	0

Table 8. Temperature Sensitivity Data, DOT Repair Mix

Run Order	Age, hrs	Curing Temperature, °F	Mix Temperature, °F	DOT Repair Mix			
				Compressive		Slant Shear Bond	
				Load, lbs	Stress, psi	Load, lbs	Stress, psi
1	13.0	77.0	77.0	88,040	12,455	10,860	770
2	15.5	100.0	100.0	43,360	6,135	25,300	1,790
3	24.0	77.0	77.0	90,620	12,820	18,990	1,345
4	24.0	100.0	40.0	37,980	5,375	32,900	2,330
5	12.0	40.0	77.0	68,870	9,745	45,320	3,205
6	1.5	77.0	100.0	38,860	5,500	8,460	600
7	24.0	40.0	100.0	75,820	10,725	4,390	310
8	1.5	40.0	40.0	820	115	640	45
9	10.5	77.0	40.0	66,940	9,470	13,920	985
10	24.0	40.0	40.0	63,840	9,030	34,390	2,435
11	1.5	100.0	77.0	40,570	5,740	30,530	2,160
12	1.5	40.0	100.0	64,740	9,160	4,180	295
13	13.0	77.0	77.0	86,010	12,170	24,460	1,730
14	15.5	100.0	100.0	24,840	3,515	30,100	2,130
15	24.0	77.0	77.0	84,300	11,925	24,010	1,700
16	24.0	100.0	40.0	43,620	6,170	44,070	3,120
17	12.0	40.0	77.0	73,900	10,455	9,170	650
18	1.5	77.0	100.0	53,710	7,600	8,700	615
19	24.0	40.0	100.0	55,290	7,820	3,310	235
20	1.5	40.0	40.0	1,150	165	810	55

Table 9. Temperature Sensitivity Data, Futura 15

Run Order	Age, hrs	Curing Temperature, °F	Mix Temperature, °F	Futura 15			
				Compressive		Slant Shear Bond	
				Load, lbs	Stress, psi	Load, lbs	Stress, psi
1	13.0	77.0	77.0	22,765	3,220	7,515	530
2	15.5	100.0	100.0	36,330	5,140	16,110	1,140
3	24.0	77.0	77.0	33,060	4,675	1,495	105
4	24.0	100.0	40.0	40,000	5,660	26,750	1,895
5	12.0	40.0	77.0	19,670	2,785	2,250	160
6	1.5	77.0	100.0	14,660	2,075	4,820	340
7	24.0	40.0	100.0	19,500	2,760	10,750	760
8	1.5	40.0	40.0	4,900	695	4,060	285
9	10.5	77.0	40.0	25,000	3,535	14,500	1,025
10	24.0	40.0	40.0	31,250	4,420	19,250	1,360
11	1.5	100.0	77.0	13,335	1,885	2,140	150
12	1.5	40.0	100.0	7,640	1,080	3,610	255
13	13.0	77.0	77.0	24,895	3,520	8,965	635
14	15.5	100.0	100.0	35,690	5,050	15,860	1,120
15	24.0	77.0	77.0	33,185	4,695	11,550	815
16	24.0	100.0	40.0	40,250	5,695	28,750	2,035
17	12.0	40.0	77.0	19,235	2,720	4,520	320
18	1.5	77.0	100.0	17,170	2,430	5,290	375
19	24.0	40.0	100.0	2,500	355	7,000	495
20	1.5	40.0	40.0	Not Set	0	Not Set	0

Table 10. Temperature Sensitivity Data, PaveMend 15

Run Order	Age, hrs	Curing Temperature, °F	Mix Temperature, °F	Pavemend 15			
				Compressive		Slant Shear Bond	
				Load, lbs	Stress, psi	Load, lbs	Stress, psi
1	13	77	77	23,040	3,260	26,340	1,865
2	16	100	100	1,870	265	3,645	260
3	24	77	77	24,565	3,475	23,505	1,665
4	24	100	40	22,775	3,220	17,800	1,260
5	12	40	77	21,035	2,975	20,495	1,450
6	2	77	100	815	115	845	60
7	24	40	100	11,660	1,650	5,850	415
8	2	40	40	2,175	310	1,730	120
9	11	77	40	23,415	3,315	19,045	1,350
10	24	40	40	9,295	1,315	10,250	725
11	2	100	77	1,550	220	2,670	190
12	2	40	100	800	115	790	55
13	13	77	77	23,375	3,305	28,975	2,050
14	16	100	100	2,030	285	3,645	260
15	24	77	77	24,780	3,505	26,785	1,895
16	24	100	40	22,700	3,210	18,520	1,310
17	12	40	77	21,525	3,045	22,295	1,580
18	2	77	100	890	125	865	60
19	24	40	100	12,145	1,720	6,470	460
20	2	40	40	Not Set	0	Not Set	0

The results from the compression test experiments were fitted to a second-order regression model with interaction terms of the following form:

$$f_c = C_0 + C_1 \log t + C_2 (\log t)^2 + C_3 T_c + C_4 T_c^2 + C_5 T_m + C_6 T_m^2 + C_7 T_C \log t + C_8 T_m \log t + C_9 T_c T_m \quad (4)$$

where

fc	=	compressive strength in psi
t	=	age in hours
Tc	=	curing temperature in °F
Tm	=	mixing temperature in °F
Ci	=	regression coefficients

The regression coefficients for compressive strength are presented in Table 11. As expected, the results indicate compressive strength is directly proportional to the age of the material and curing temperature for all materials. For all materials, various secondary interactions between age and temperature were found to be significant.

Table 11. Compressive Strength Model Coefficients

Product	C_0	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9
DOT	-30620	11290	0	385.0	-3.144	636.2	-3.640	0	-100.5	0
10-61	-845.0	1172	0	24.561	0	0	-0.0887	-19.52	16.04	0
Futura 15	-12680	5780	0	-6.696	0	0	0	0	-46.85	0.5275
PaveMend 15	-11870	694.8	0	195.8	-1.010	233.0	-1.415	12.02	0	-0.7974

Figure 20 through Figure 23 present plots of the compressive strength versus age from the regression models for the four materials given various scenarios of mixing and curing temperatures. The first graph in each figure presents the scenario of equal mixing and curing temperatures of 40, 77, and 100 °F. The three lower graphs show the model predictions for curing temperatures of 40, 77, and 100 °F with mixing temperatures of 40, 77, and 100 °F for each curing temperature. The premise behind these plots is that field users will have no control over curing temperature, but may control mixing temperature by storing materials in a temperature-controlled environment until just before mixing.

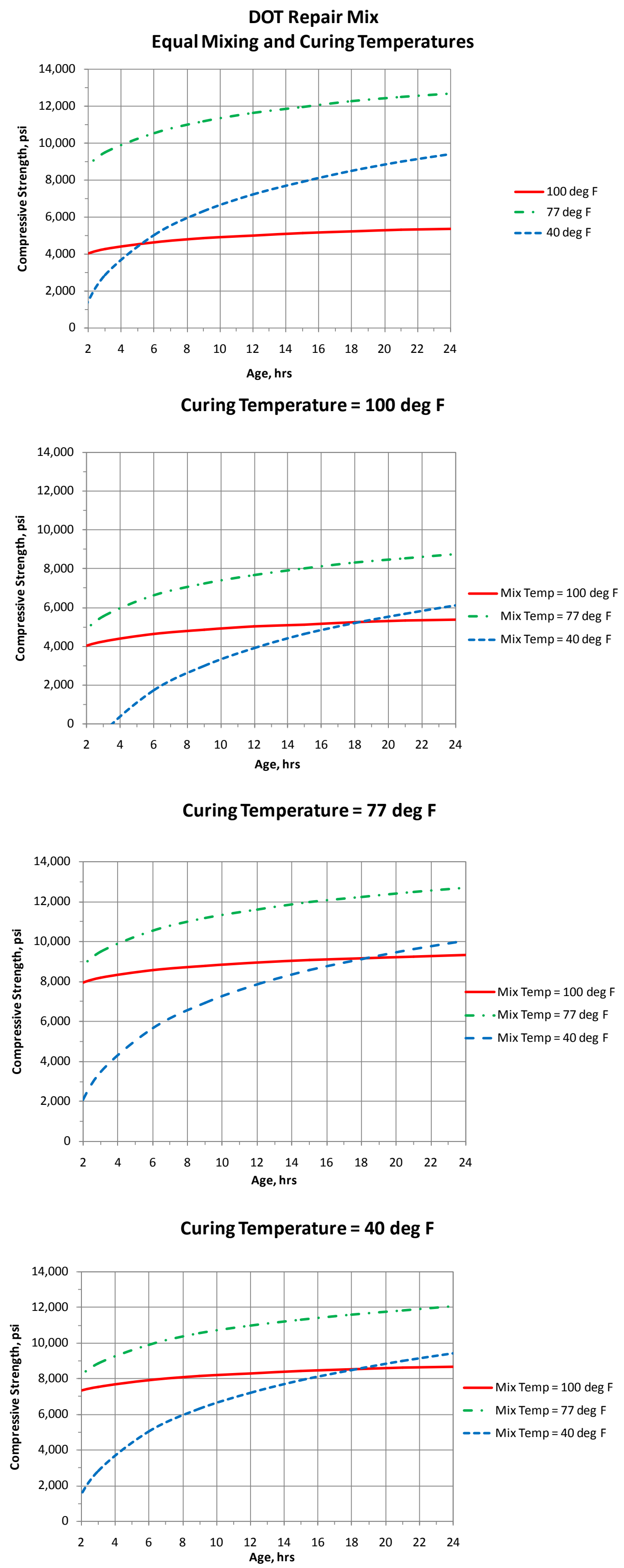

Figure 20. Predicted Compressive Strength Gain Curves, DOT Repair Mix

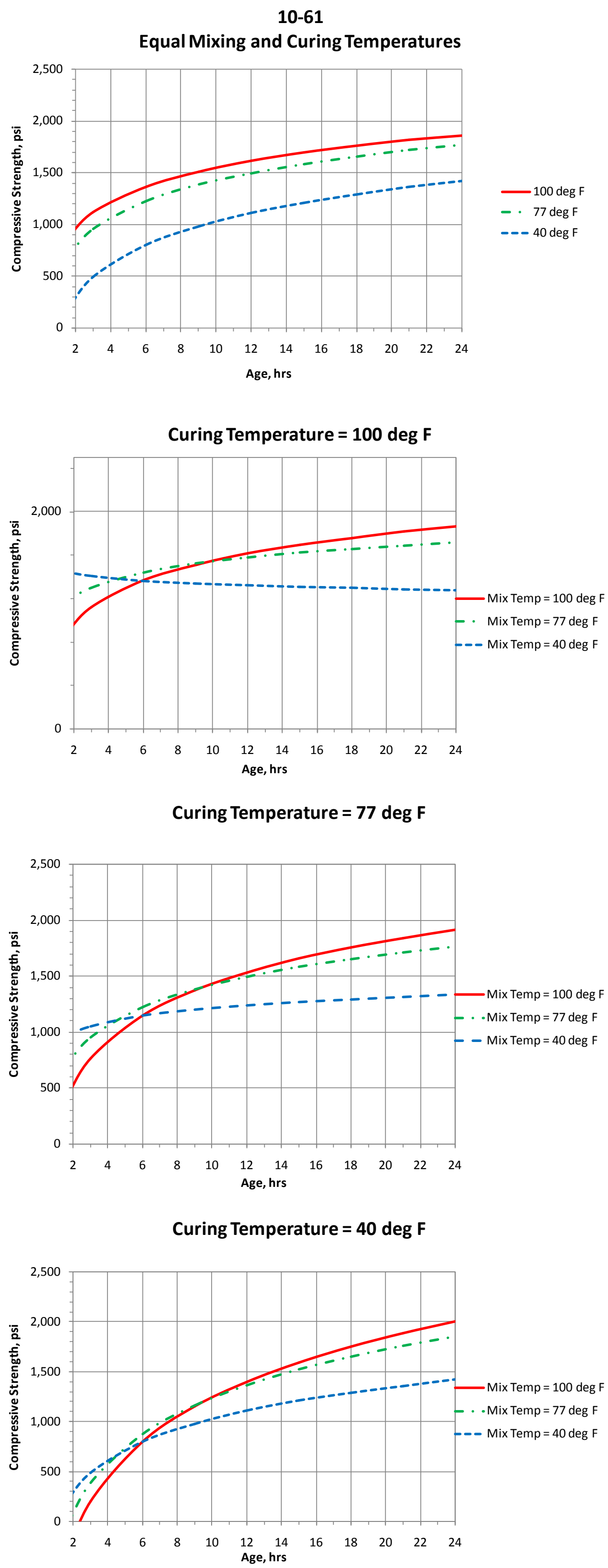

Figure 21. Predicted Compressive Strength Gain Curves, 10-61 Rapid Set

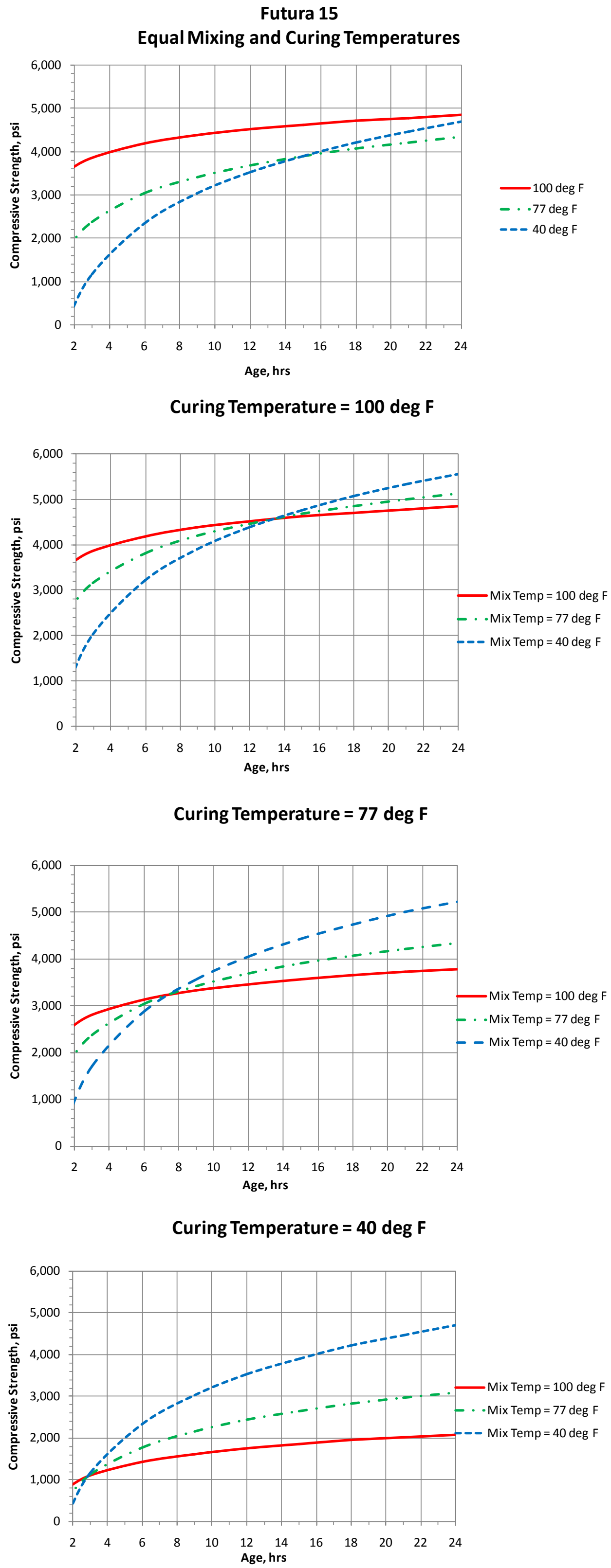

Figure 22. Predicted Compressive Strength Gain Curves, Futura 15

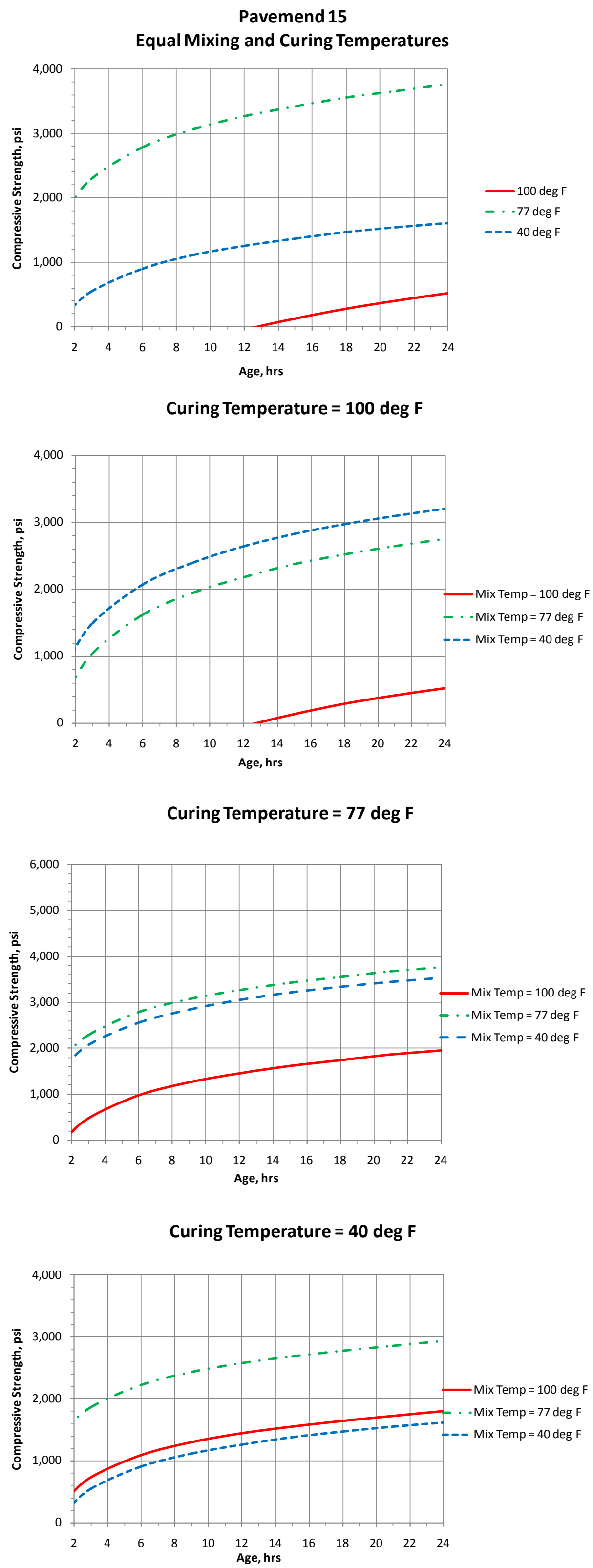

Figure 23. Predicted Compressive Strength Gain Curves, PaveMend 15

The most striking conclusion from these models, based on data from a designed experiment, is that the mixing and placing temperatures have a significant effect on the early-age compressive strength gain. Comparing the various materials shows that these effects vary from material to material, and a general trend is not readily evident across all the materials. It is expected that increased temperature would speed up the hydration reaction, and result in increased compressive strength at early age. This trend seems to be apparent for 10-61 and Futura 15, while DOT Repair Mix and PaveMend 15 are negatively impacted by high temperatures. More information on the constituent materials and additional research would need to be conducted to determine the causes of these effects.

In a similar manner, the results from the slant shear experiments were fitted to a second-order regression model with interactions of the following form:

$$f_b = C_0 + C_1 \log t + C_2 (\log t)^2 + C_3 T_c + C_4 T_c^2 + C_5 T_m + C_6 T_m^2 + C_7 T_C \log t + C_8 T_m \log t + C_9 T_c T_m \quad (5)$$

where

fb	=	slant shear bond strength in psi
t	=	age in hours
Tc	=	curing temperature in °F
Tm	=	mixing temperature in °F
Ci	=	regression coefficients

The regression coefficients for bond strength are presented in Table 12. While there are some differences in interaction term significance, overall the trends for the bond strength are similar to those for compressive strength. Figure 20 through Figure 27 present plots of the same scenarios as plotted for the compressive strength models.

Table 12. Bond Strength Model Coefficients

Product	C_0	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9
DOT	-700	2717	0	-141.6	1.137	143.6	-0.9056	0	-28.57	0
10-61	-390	490.9	0	11.296	0	0	-0.0453	-7.418	7.704	0
Futura 15	-662	1751	0	7.0596	0	0	0.0511	0	-15.66	0
PaveMend 15	-6340	364.5	0	74.88	-0.5454	152.6	-1.033	11.30	-5.323	-0.1566

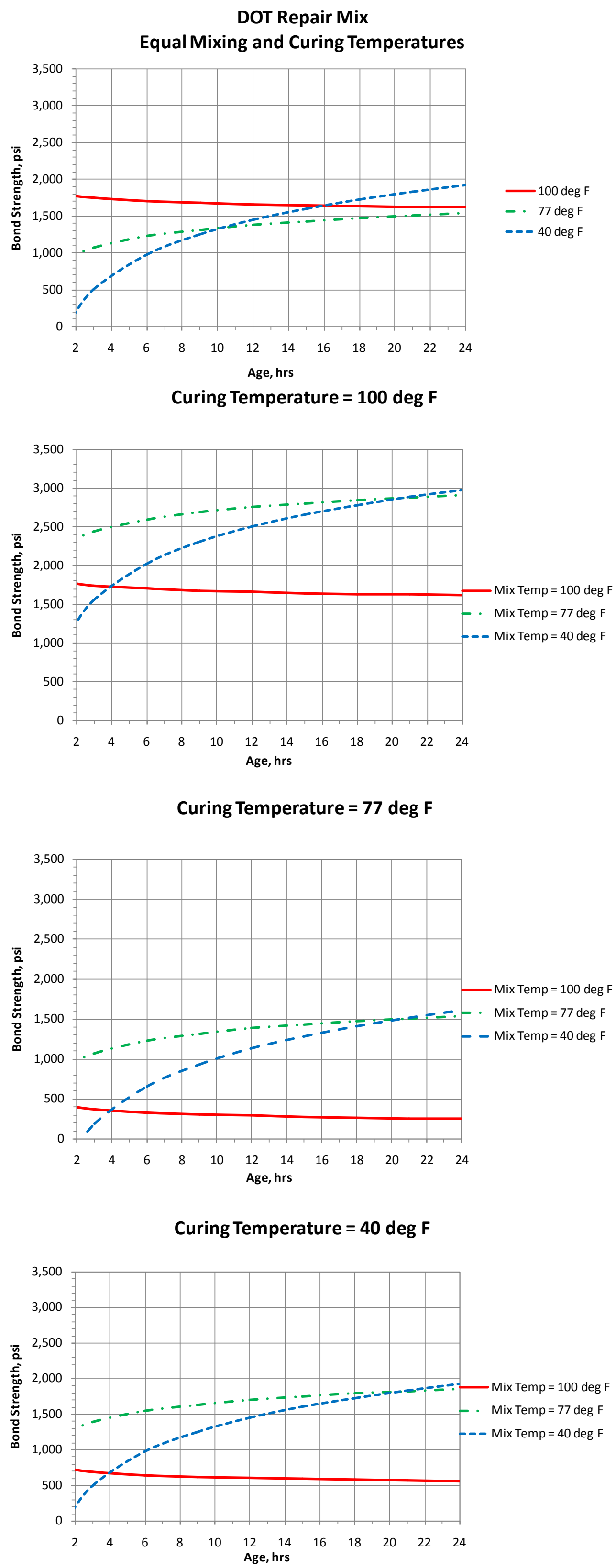

Figure 24. Predicted Bond Strength Gain Curves, DOT Repair Mix

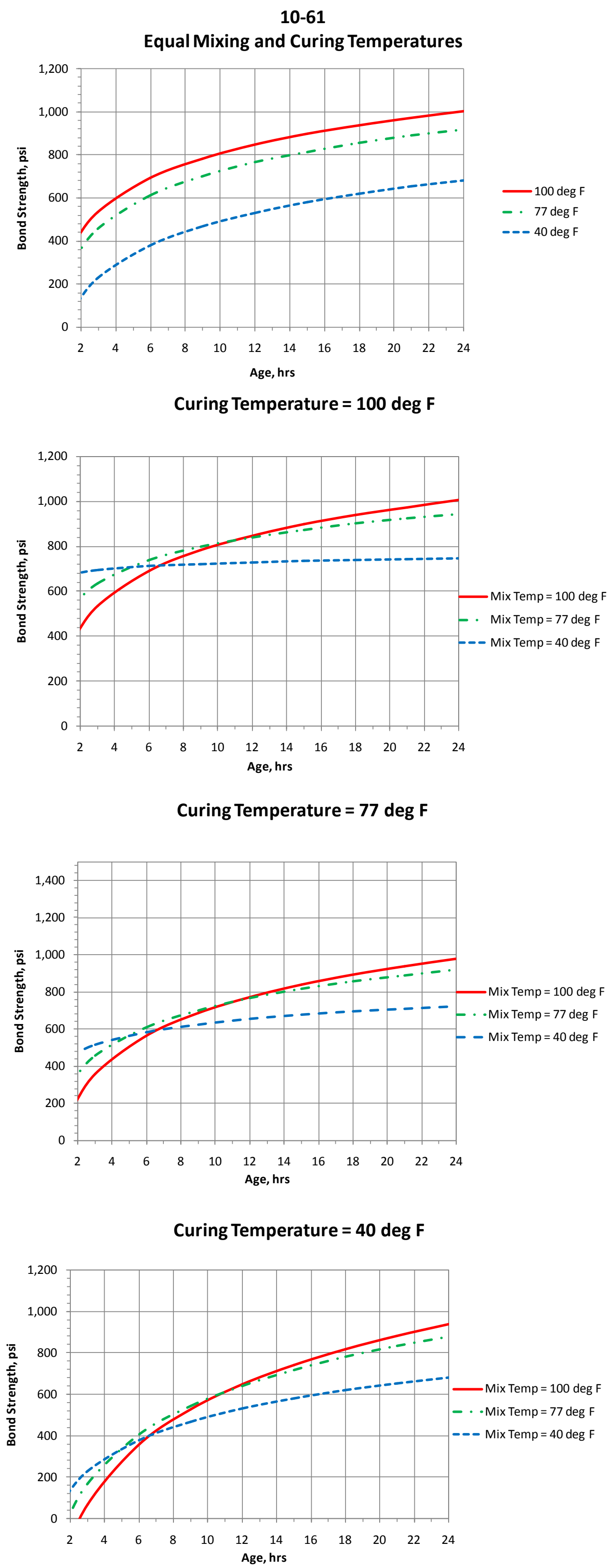

Figure 25. Predicted Bond Strength Gain Curves, 10-61 Rapid Set

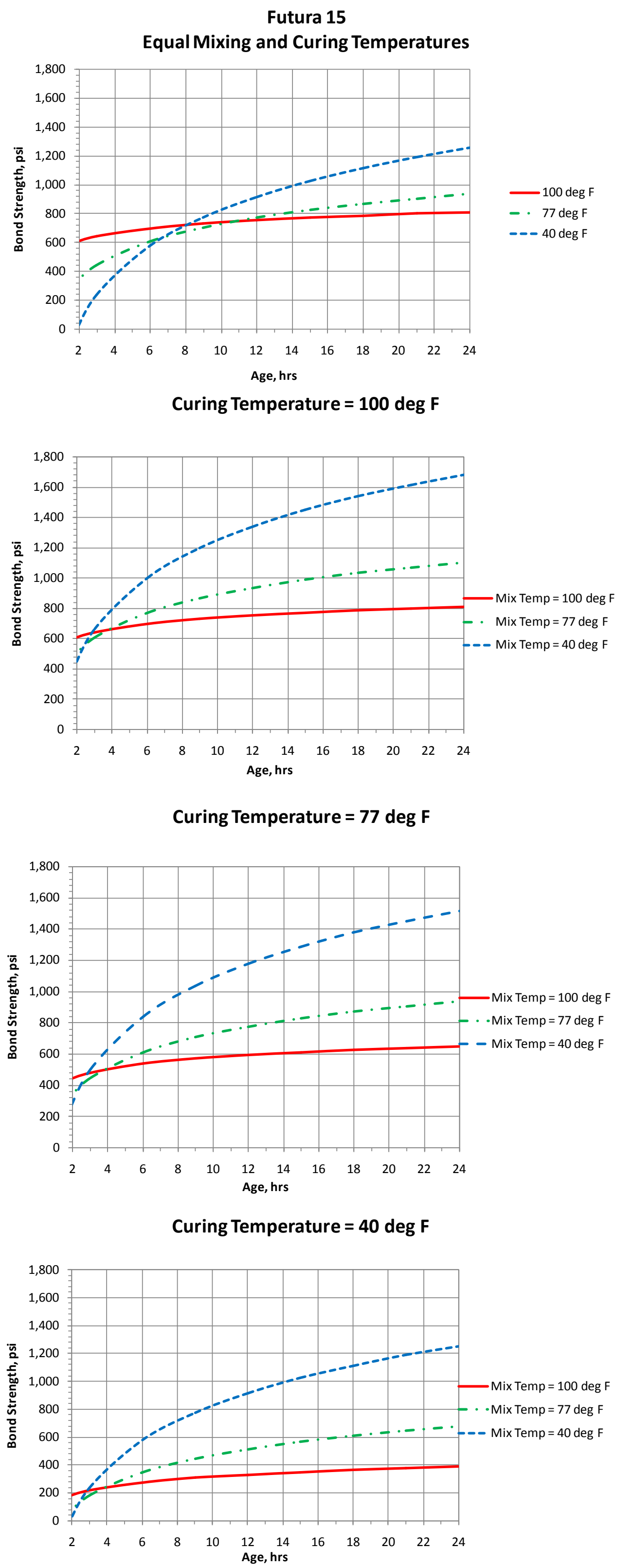

Figure 26. Predicted Bond Strength Gain Curves, Futura 15

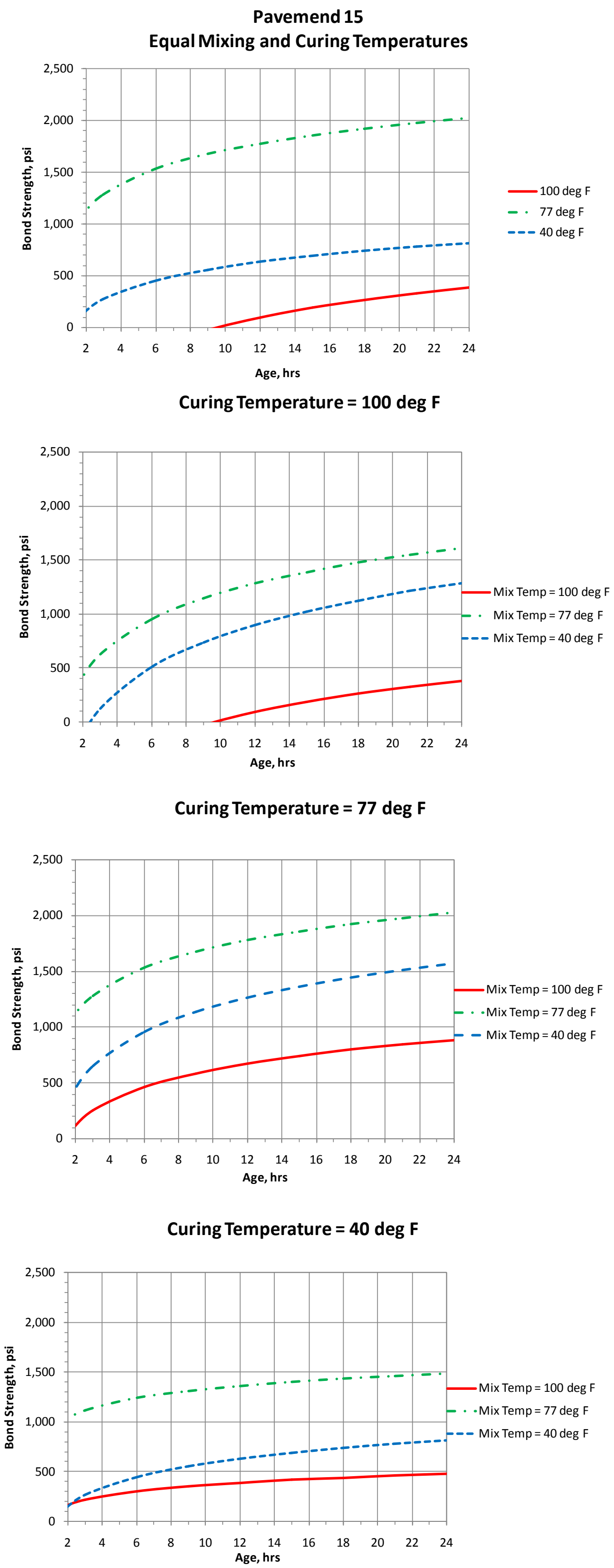

Figure 27. Predicted Bond Strength Gain Curves, PaveMend 15

6. CONCLUSIONS

6.1. Compressive Strength

All material specimens were subjected to compressive strength testing and analysis following the ASTM C39 protocol. The greatest strength gain exhibited by the Rapid Set DOT Mix, SikaQuick 2500, Premium Patch and HD-50 Rapid Set materials. These materials attained compressive strength values of more than 2,500 psi in less than two hours cure time.

Materials resulting in the slowest compressive strength gain included PavePatch 3000, PaveMend TR and PaveMend 15; these materials only achieved a maximum of 2,700 psi within a 24 hour time interval.

6.2. Flexural Strength

Specimens underwent flexural strength testing in accordance with ASTM C78 protocol. The materials boasting the greatest flexural strength of more than 700 psi within 1.5 hours include SikaQuick 2500, Premium Patch, and Rapid Set DOT Mix. PaveMend VR and PaveMend 15 both failed to achieve more than 450 psi after 24 hours; PaveMend TR adhered to the mold apparatus and could not be tested.

6.3. Slant Shear Bond Strength

ASTM C882 was performed on all samples to evaluate their bond strength potential to OPC. Of the materials tested, SikaQuick 2500, Rapid Set DOT Mix, 10-61 Rapid Set and HD-50 performed the best with results exceeding 800 psi at the 1.5 hour time interval. Futura 15 performed the worst with values below 600 psi after a cure time of 24 hours.

6.4. Split Tensile Strength

As per ASTM C496, all materials were molded into 3-in diameter × 6-in long cylinders and tested for their individual tensile strengths. Rapid Set DOT Mix, SikaQuick 2500 and Premium Patch all provided results beyond 350 psi in under two hours. Veraspeed, PaveMend TR and PaveMend 15 produced less than 150 psi at the 24 hour test interval. The final results for Futura 15 could not be obtained as all samples made of this material broke during compression at all time intervals.

6.5. Additional Testing Regimes

6.5.1. Temperature Sensitivity

The four materials were down-selected from the original eleven for further testing. Down-selected materials were then subjected to varying temperatures during both mixing and curing processes to assess their sensitivity to thermal loading outside of normal ambient. Three separate temperature regimes were selected for each specimen and the temperatures were kept constant during both mixing and curing phases. The temperatures selected were 40, 77 and 100 °F.

It was determined that while the user may not be capable of controlling the ambient curing environment, they could easily control and monitor the mixing temperatures by storing the individual materials accordingly prior to use. It was also theorized that an increase in temperature would positively aid in the hydration process and thus, increase early-age strength values.

Resulting data concluded that while mixing and placing temperature variances had a significant effect upon the early compressive strength gain for all tested materials, an evident trend for all materials could not be established. The materials 10-61 and Futura 15 both followed this logic, however, the Rapid Set DOT Mix and PaveMend 15 showed decreases in compressive strength when subjected to high temperatures.

6.5.2. Effects of Variable Water

The four down-selected materials, when tested for 110 and 125 percent water using ASTM C39 above manufacturers' recommendations, exhibited water sensitivity especially during early ages ($\leq$ 4 hours).

The material found to be least sensitive to additional water was Rapid Set DOT Mix, while Futura 15 was the most sensitive with a decrease of approximately 2,000 psi at two hours and 110 percent. Adding 125 percent water caused the strength of Futura 15 to decrease by 1,700 psi at 24 hours. The Rapid Set DOT Mix decreased by the following values at 24 hours relative to water percentage: 1,200 at 110 percent and 2,000 at 125 percent water.

6.5.3. Field Loading

Prior to the material testing study, testing to determine the best suited repair method and equipment for advanced spall repair was conducted. Three different excavation methods were employed and timed for efficiency determination. The spalls were created by either sawcutting, jackhammering or hydraulically-controlled cold planing. The voided areas were prepared and were left vacant in anticipation of this material testing phase.

A final test scenario of this study was field implementation and load trafficking. The final selected four materials were each placed into one of the three different excavation method voids and allowed to fully cure prior to loaded traffic. The load was traversed for a total of 1,500 passes by an F-15 cart loaded to 32,500 lbs (14,742 kg) as stated in Section 4.1.6. Each test area was visually inspected and crack mapped at specific trafficking intervals to assess the material durability and shrinkage potential. Deflection measurements or load transfer mechanisms were not required for the purpose of this study.

7. RECOMMENDATIONS

- Based on empirical data and materials characteristics testing, it is recommended that either the Rapid Set DOT Mix or SikaQuick 2500 material be used for rapid-setting spall repairs.

- Materials are water sensitive as each manufacturers recommendation should be followed to ensure superior performance.

- The cold planer method is the recommended method of spall preparation.

- Additional tests should be performed using alternative materials not yet tested in an effort to broaden the applicable base of available and newer repair materials.

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LIST OF SYMBOLS, ABBREVIATIONS, AND ACRONYMS

ACI	American Concrete Institute
AFRL	Air Force Research Laboratory
ASR	alkali-silica reaction
ASTM	American Society for Testing and Materials
bar	unit of pressure
CTI	CeraTech Incorporated
e.g.	for example
ETL	Engineering Technical Letter
FOD	foreign object debris
ft	foot/feet
hrs	hours
in	inch
kg	kilograms
lbs	pounds
m	meter(s)
mm	millimeter(s)
OPC	ordinary Portland cement
psi	pounds per square inch
SSD	saturated surface dry
°F	temperature in degrees Fahrenheit
%	percent